Plasma Rotation Driven by Static Nonresonant Magnetic Fields

Presented by
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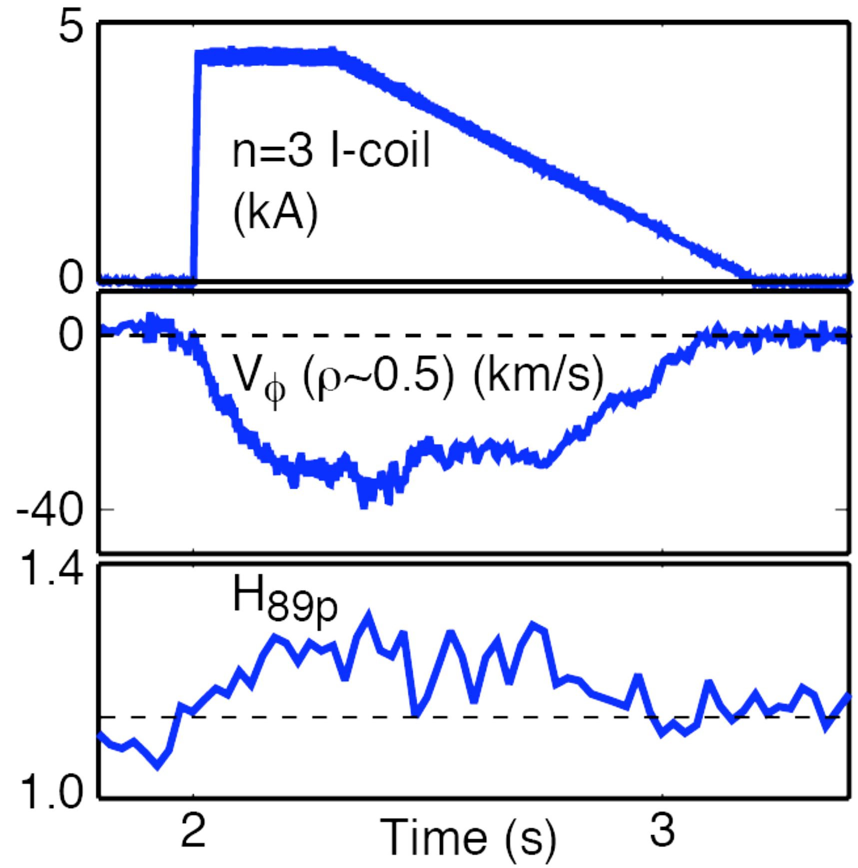
in collaboration with
K.H. Burrell, J.S. deGrassie, G.L. Jackson, R.J. La Haye, M. Lanctot, J-k. Park, H. Reimerdes, M.J. Schaffer, W.M. Solomon, E.J. Strait, and the DIII-D Team



Presented at the
US-Japan Workshop on MHD Control
University of Texas at Austin, Texas

November 23–25, 2008

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GENERAL ATOMICS

Neoclassical Torque From NRMFs Due to Increased Collisional Transport

- **Extensive literature coverage of NRMF torque since early 70s**
  - **NRMFs produce "ripples" in the magnetic field strength**
    - Particles can be trapped in new magnetic wells
    - Orbits of banana-trapped particles can be significantly modified
  - **Both effects cause increased collisional transport, non-ambipolar radial ion particle flux**

    => radial "return" current evolves to maintain neutrality

    => toroidal torque = $J_r x B_\theta$

Neoclassical Offset Rotation Associated With Torque Driven by NRMFs

- **New development:**

J. D. Callen, Univ. of Wisconsin

in collaboration with C. C. Hegna and K. C. Shaing;

stimulated by discussions with M.S. Chu, A.M. Garofalo, S.A. Sabbagh, R.J. La Haye

Integrated Modeling Meeting, General Atomics, 19 March 2003

$$\Rightarrow \frac{\partial \Omega_\zeta}{\partial t} \simeq -\mu_t (\Omega_\zeta - \Omega_0)$$

$\frac{1/\nu \text{ regime}}{\omega_t < \frac{\nu_i}{\epsilon} < \epsilon^{1/2}\omega_{ti}}$ $\quad \mu_t^{1/\nu} \simeq \omega_{ti} \frac{\# q^2}{\nu_{*i}} \left[\frac{I_\lambda}{\epsilon^{3/2}}\right], \quad \Omega_0^{1/\nu} \simeq \frac{1.17 + \frac{32.4}{13.7}}{e_i} \frac{dT_i}{d\chi} \simeq \frac{3.5}{Z_i e B_\theta R_0} \frac{dT_i}{dr}$

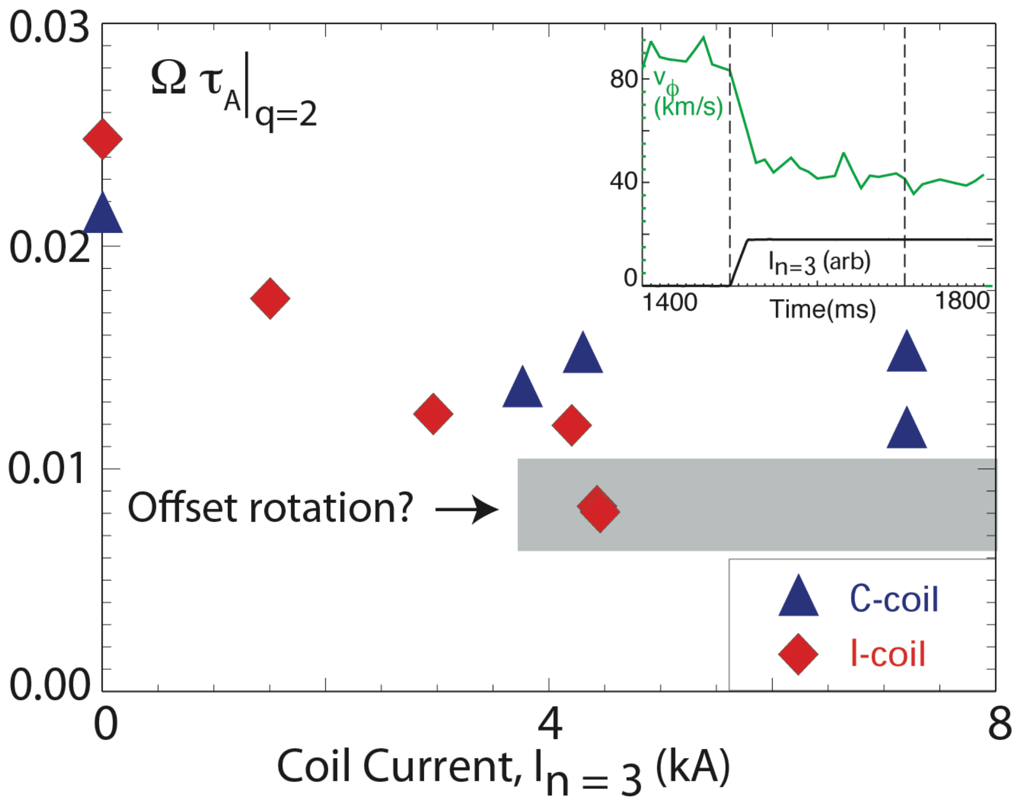
  – T_{NRMF} **drags flow to an "offset" rotation, comparable to ion diamagnetic frequency, in direction opposed to plasma current**

    - $T_{NRMF} \propto (V_\phi - V_\phi^{0,NC}), \qquad V_\phi^{0,NC} \propto (dT_i/dr)/Z_i e B_\theta$

      [Cole, Hegna, and Callen, Phys. Plasmas (2008)]

Non-resonant Braking Effect in DIII-D Was Observed to Decrease With Lower Rotation

- **n=3 braking effect seemed to saturate as braking field increased**



Driskill, et al., Bull. Am. Phys. Soc. (2005)
Jackson, et al., EPS 2006

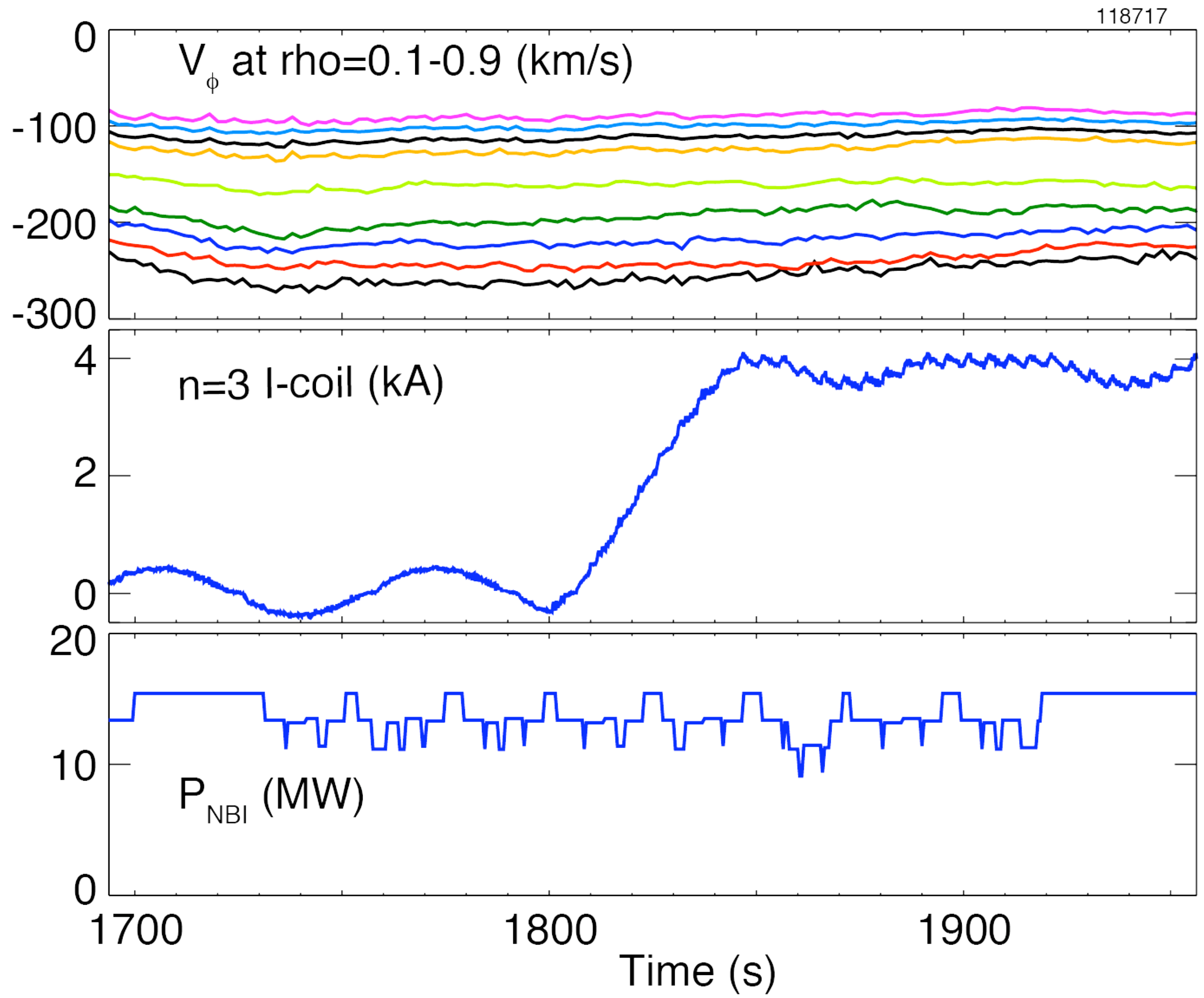
- **Saturated rotation consistent (in magnitude) with neoclassical offset rotation**

$$\Omega^{NC} \sim 2/3 \nabla T_i / (Z_i e B_\theta R)$$

- **Offset rotation in the co-Ip direction entails larger braking should be observed in reversed Ip**

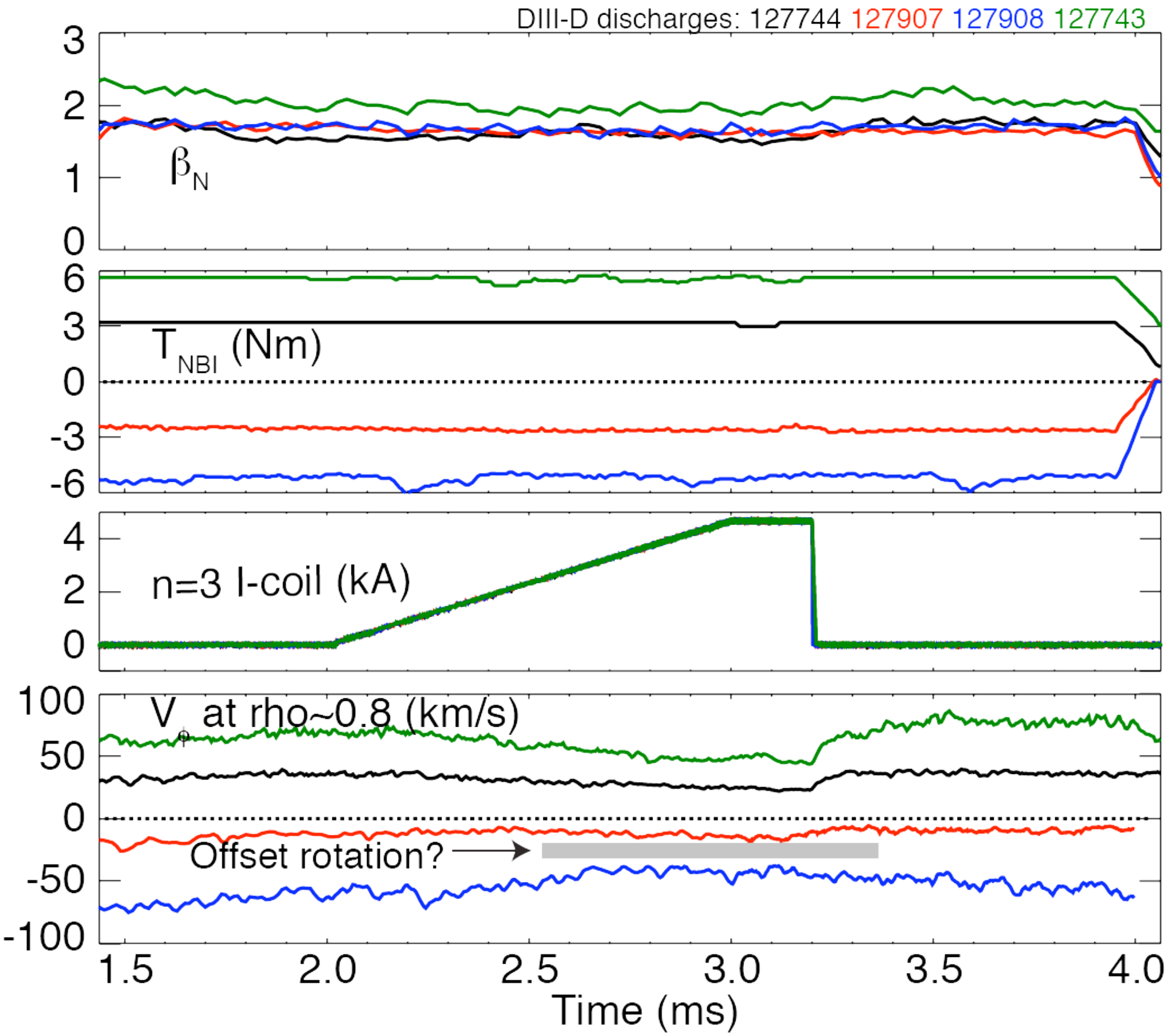
$$T_{NRF} \propto (\Omega - \Omega^{NC})$$

n=3 Experiments in DIII-D Reversed-Ip Plasmas Showed Little or No Braking



- **These results suggest Ω^{NC} is in the counter-Ip direction**

Systematic Scan of NBI Torque in 2007 Experiments Showed Little or No Effect on Slow Counter-Ip Rotation



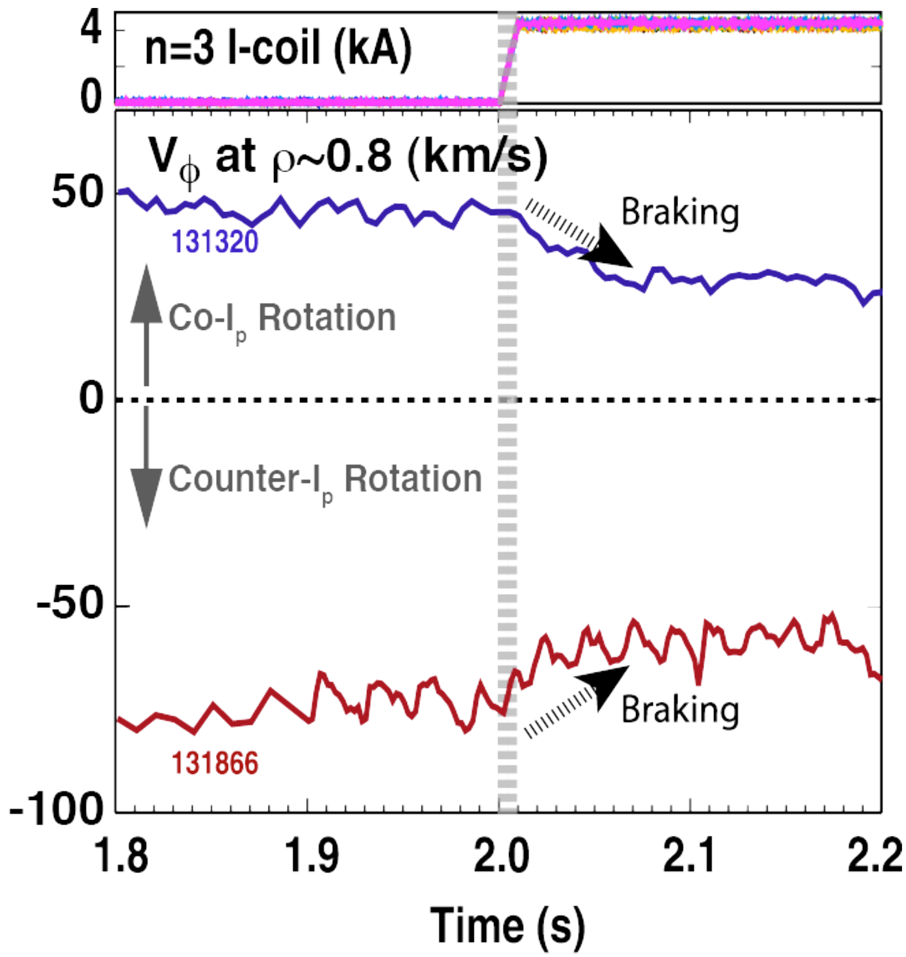
- **Broad range of NBI torque achieved by matching plasmas with normal and reversed Ip direction, in addition to varying the mix of co and counter NBI for given Ip direction**
- **Braking observed for co-rotation and fast ctr-rotation**
- **Slight acceleration observed for slow ctr-rotation**

Outline

- Evidence of offset rotation
- Comparison to neoclassical prediction
- Analysis of torque scaling
- Role of plasma response
- Implications for ITER

First Clear Evidence of Offset Rotation Associated to Nonresonant Magnetic Fields (NRMF)

- **Static *n*=3 NRMF applied to plasmas with different toroidal rotation**
  - Constant NBI torque in each discharge
- **T_{NRMF} drags flow**



First Clear Evidence of Offset Rotation Associated to Nonresonant Magnetic Fields (NRMF)

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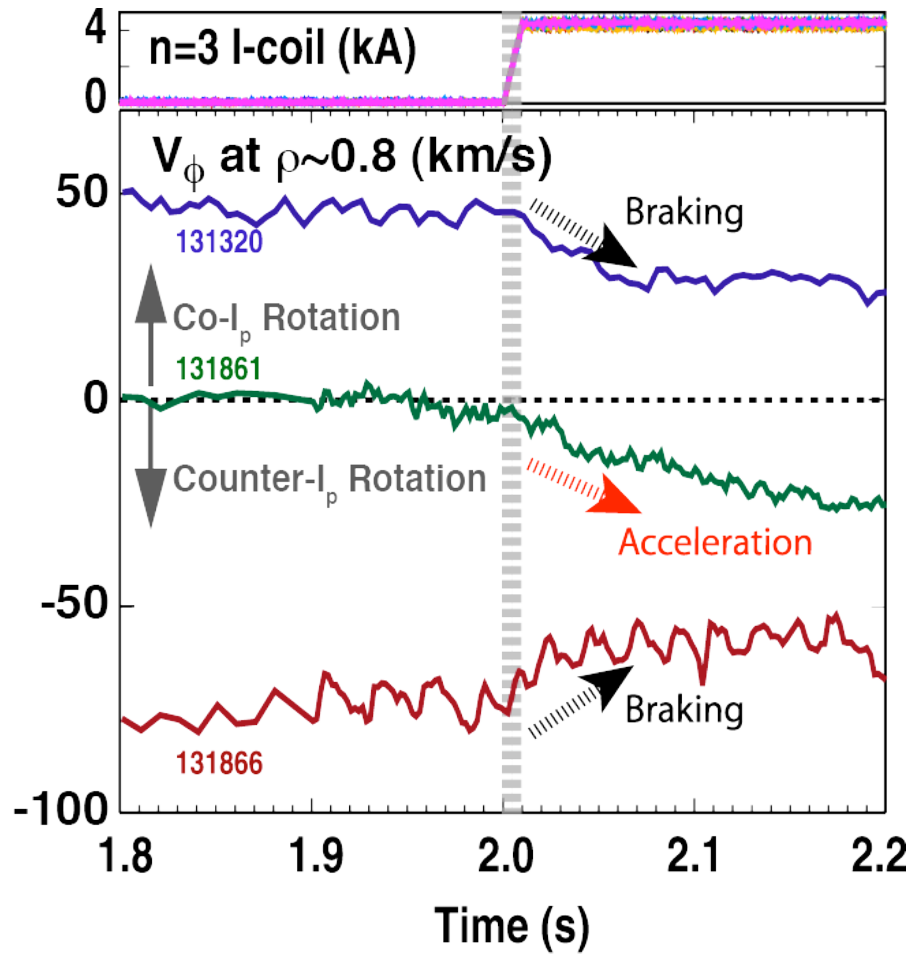
- **T_{NRMF} drags flow toward offset rotation in counter I_p direction**
  - Can lead to plasma acceleration



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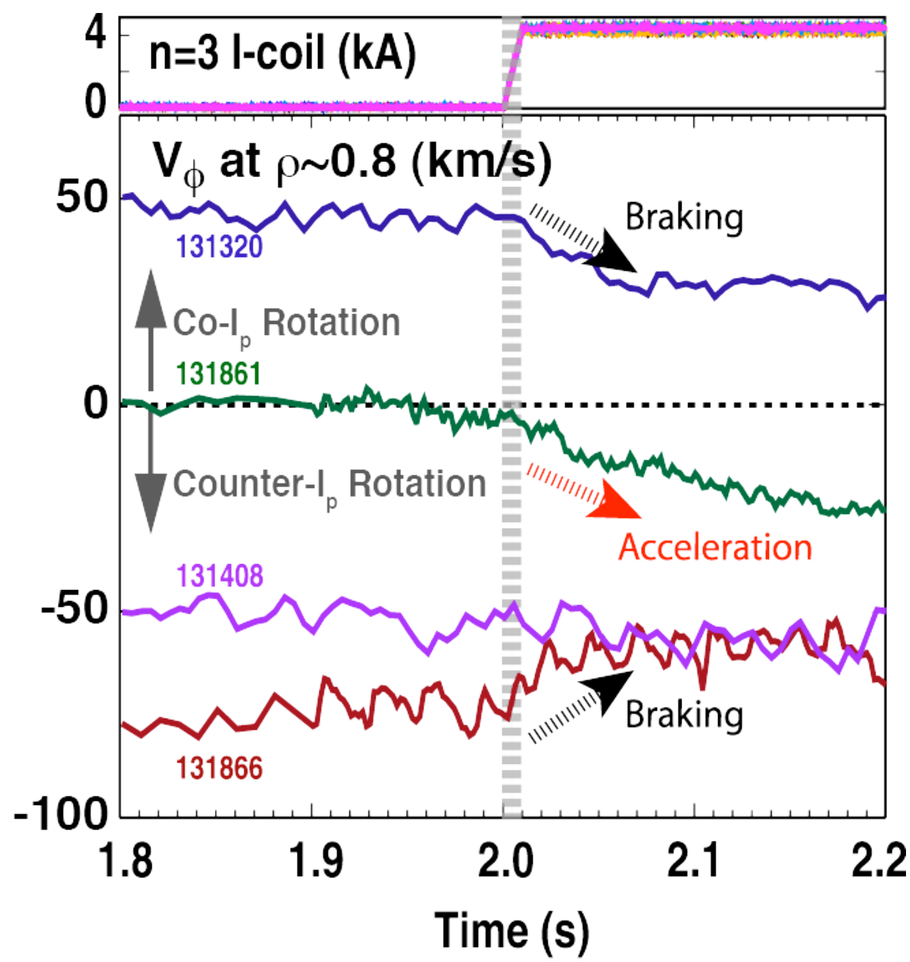

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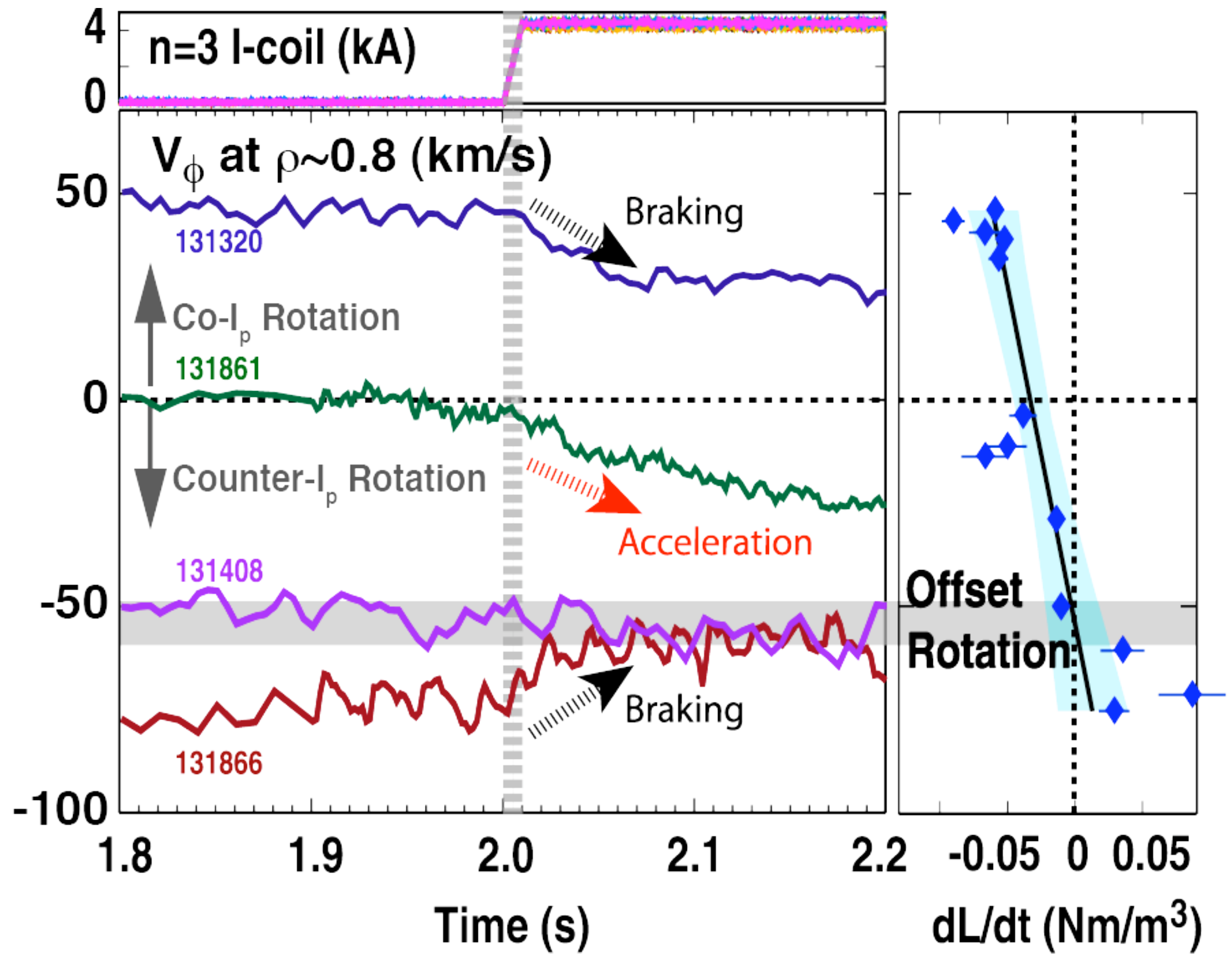
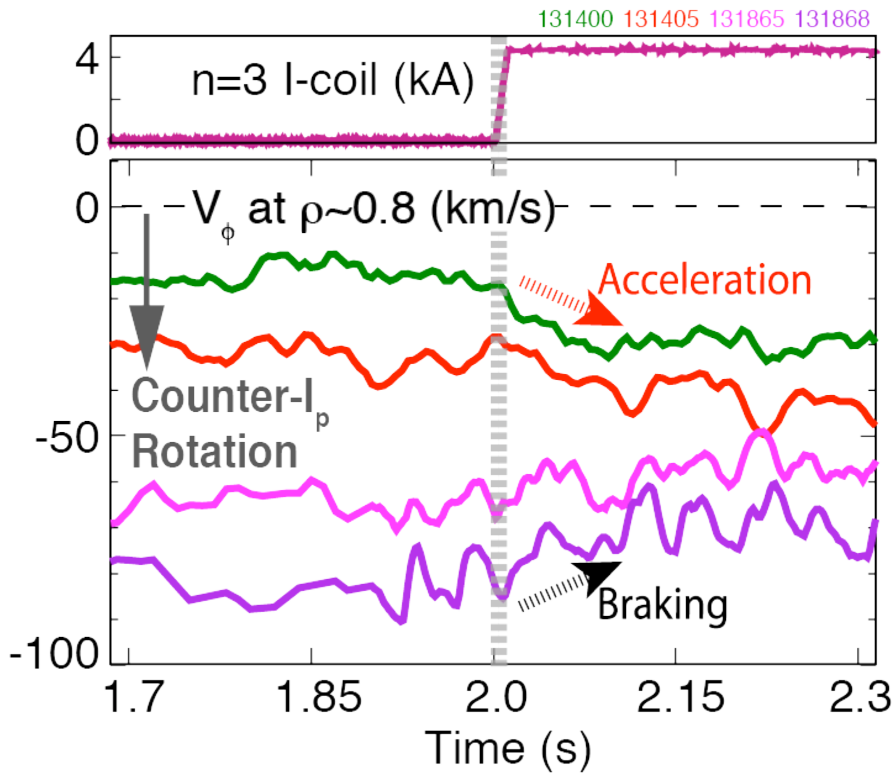
- **Static *n*=3 NRMF applied to plasmas with different toroidal rotation**
  - Constant NBI torque in each discharge
- **T_{NRMF} drags flow toward offset rotation in counter I_p direction**
  - Can lead to plasma acceleration
- **Measured torque exhibits offset linear relationship**
  - $T_{NRMF} \propto (V_\phi - V_\phi^{0,NC})$

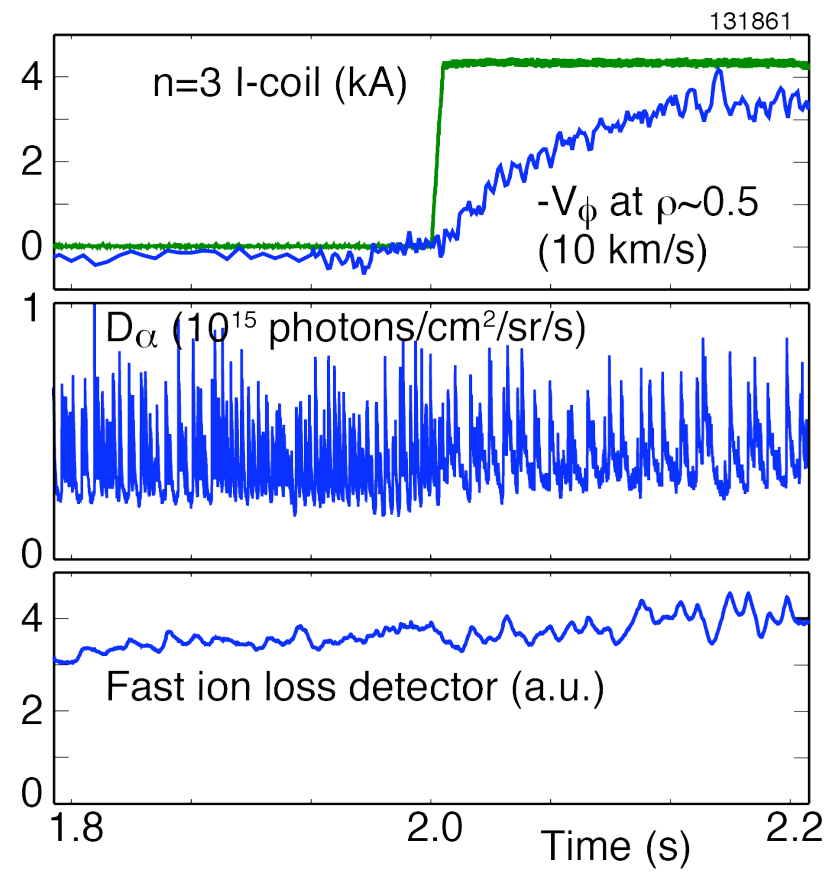


Experimental Results Consistent With Offset Rotation, Not Consistent With …

- … correcting intrinsic *n*=3 error field, since braking observed in similar discharges with higher counter-rotation

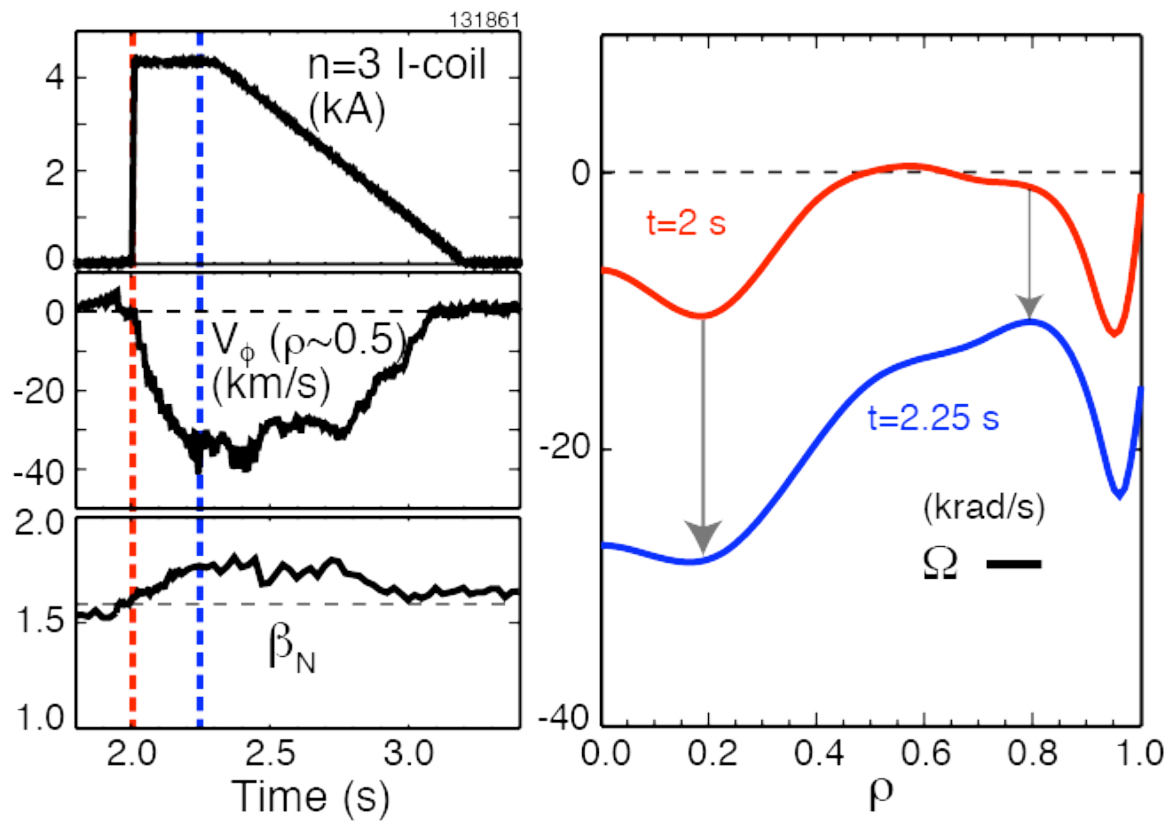


- … change in ELMing character
- … enhancement of fast ion loss



n=3 NRMF at Slow Rotation Produces Acceleration and Improvement in Global Energy Confinement

- **NBI power and torque constant during time range shown**
- **Increase of rotation observed at all minor radii in:**
  - Measured carbon impurity ion rotation



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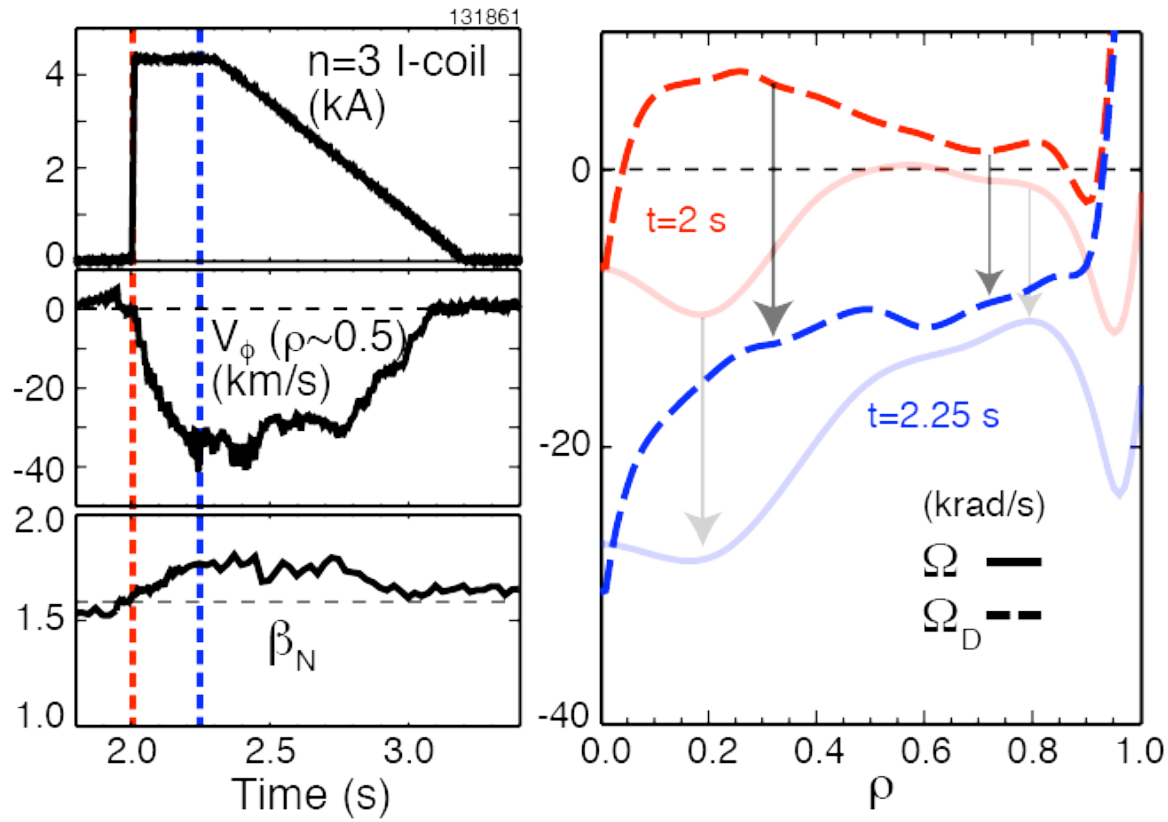
- **NBI power and torque constant during time range shown**
- **Increase of rotation observed at all minor radii in:**
  - Measured carbon impurity ion rotation
  - NCLASS calculated main ion (deuterium) rotation



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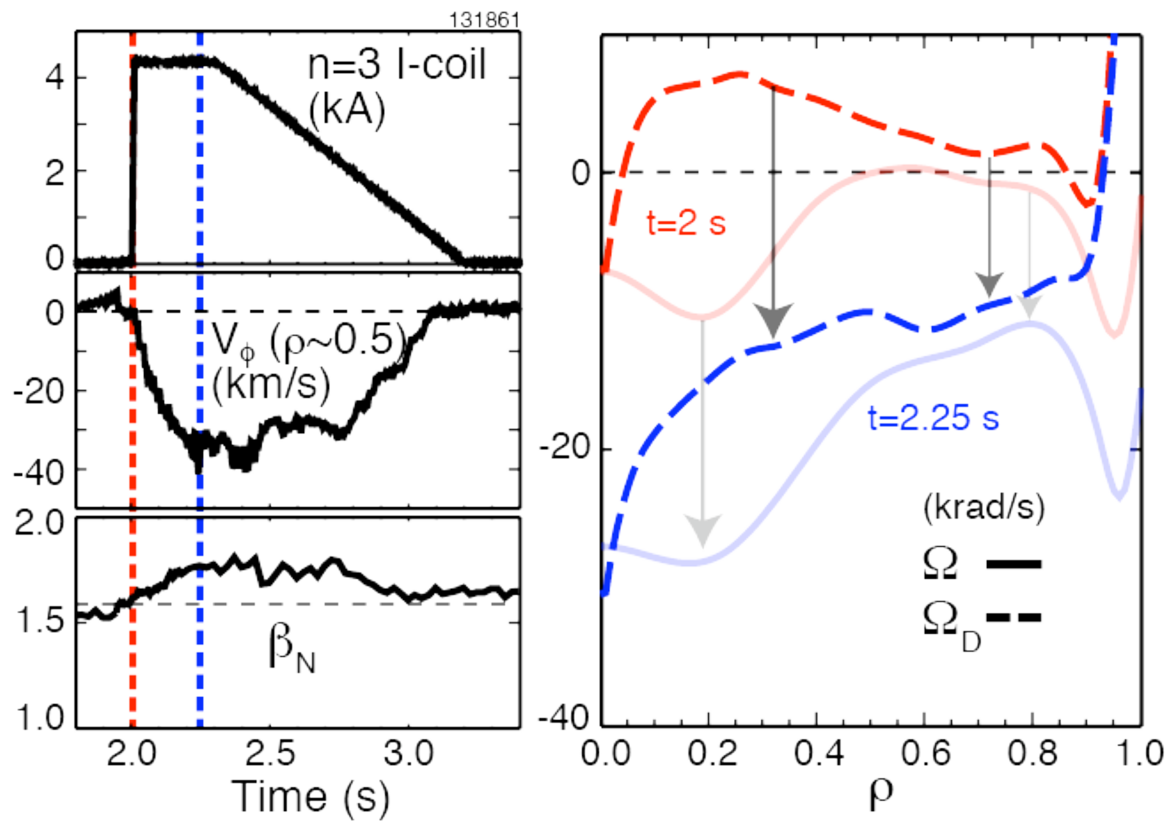
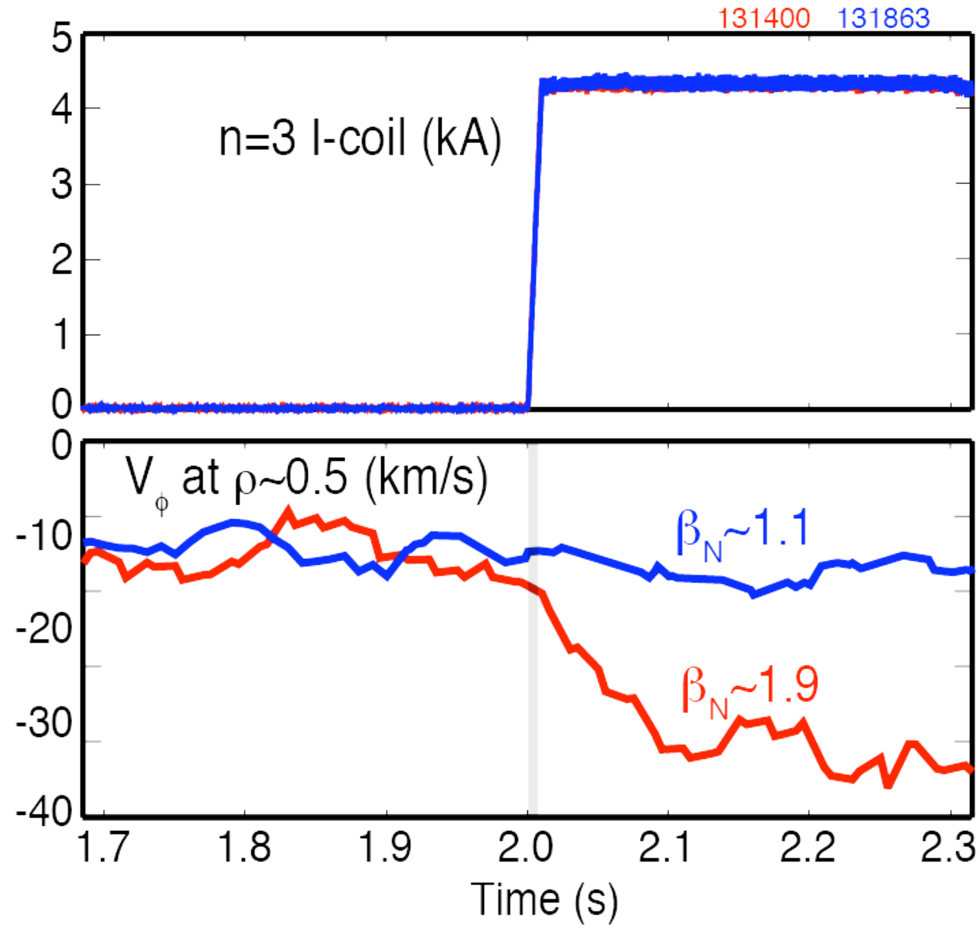


- **β_N increase consistent with *ExB* shear stabilization**
  - Small reduction in calculated ITG growth rates

Little or No Acceleration Observed at Low Plasma β

- **Slow counter-I_p rotation discharges**
- **Both NRMF torque and offset rotation may be reduced at lower β_N**
  - Discussed later



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- Evidence of offset rotation
- Comparison to neoclassical prediction
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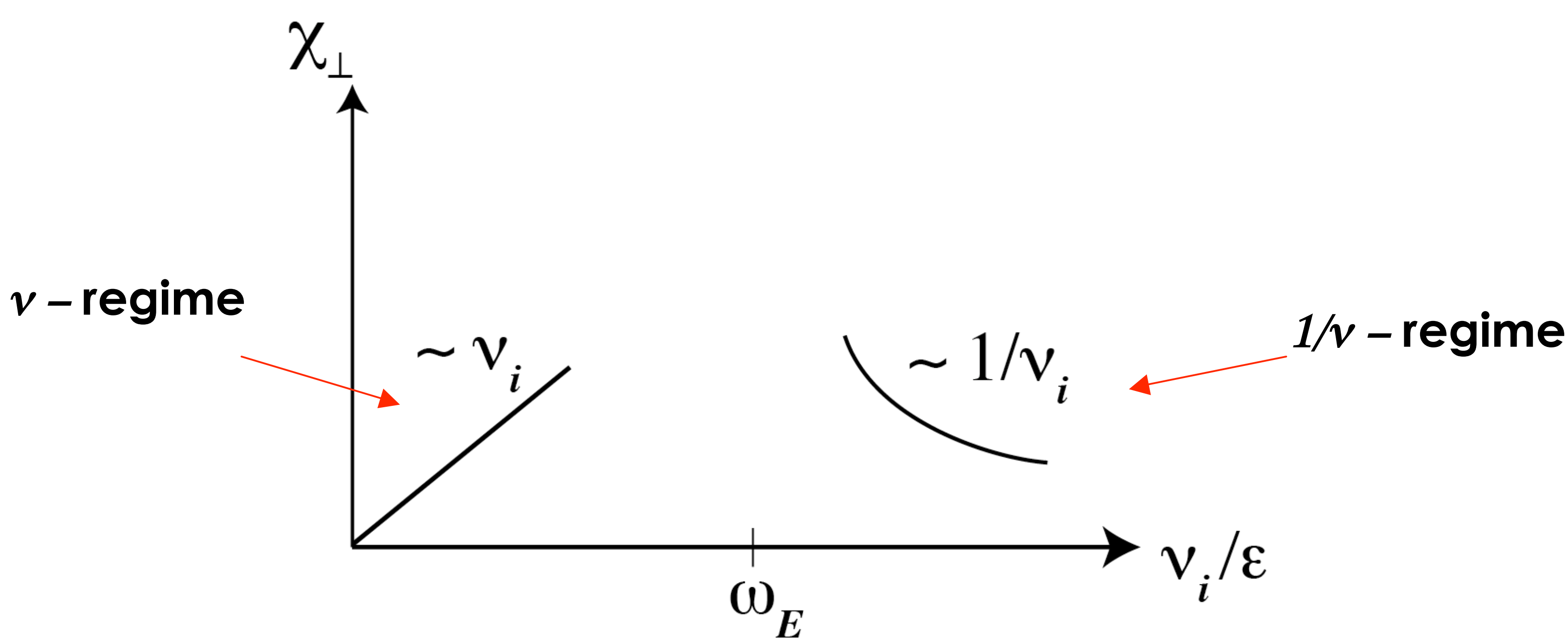
- Implications for ITER

Neoclassical NRMF Torque Is Associated With Increased Collisional Transport

- **Low ion collisionality (ν_ι) limit: transport increases as ν_ι**
  - De-correlation rate ~ banana toroidal-drift rate ~ $\omega_E = E_r/RB_\theta$
- **Higher collisionality limit: trapped particle effects diminish as $1/\nu_\iota$**



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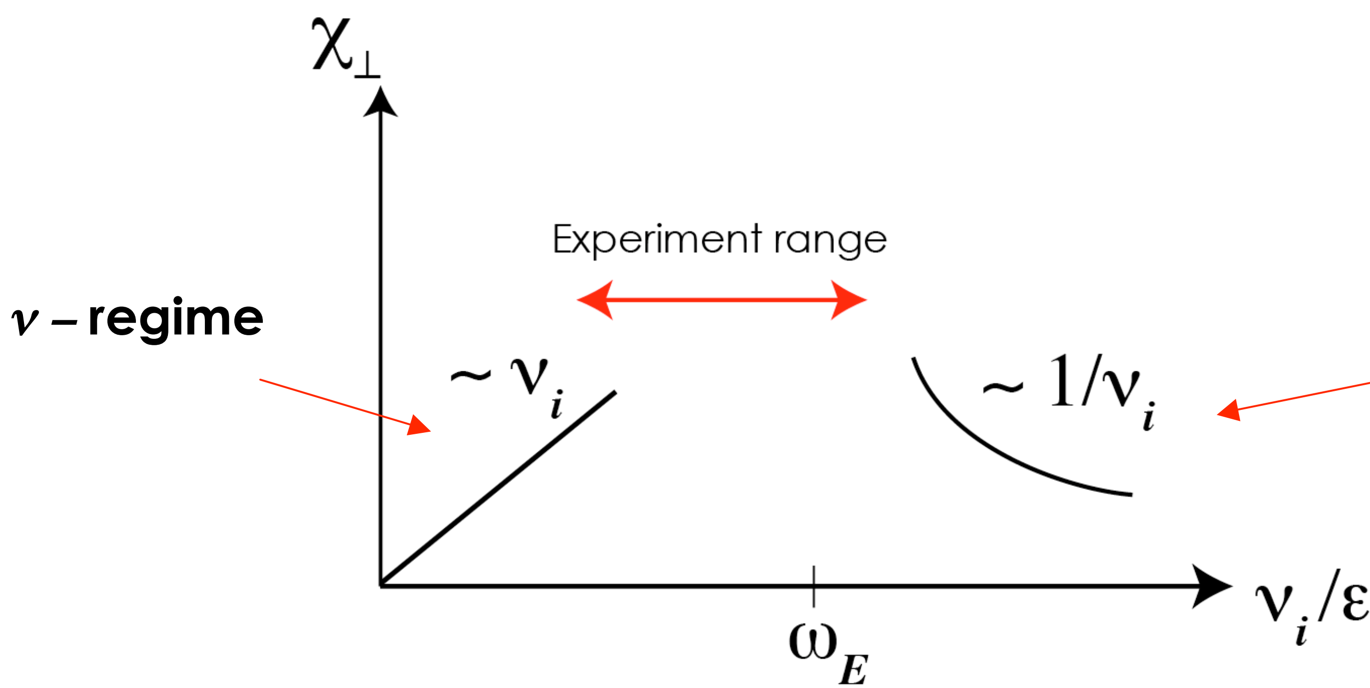
- **Detailed theory is still being developed in-between limits**

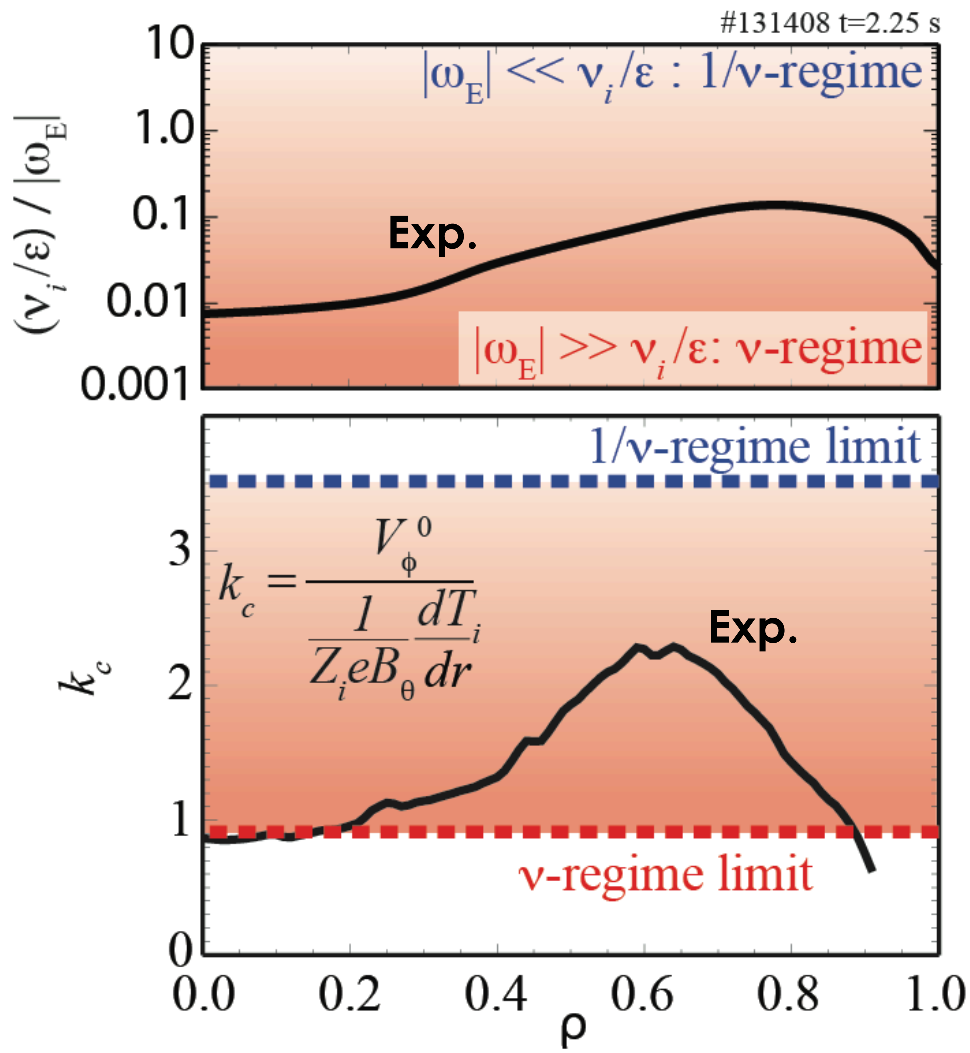


Magnitude and Radial Dependence of Offset Rotation Are Consistent with Theory

- **Neoclassical model gives offset rotation**

  $V_{\phi}^{0,NC} = k_c (dT_i/dr)/Z_i e B_{\theta}$

  with k_c depending on collisionality regime
  - ν regime limit $\rightarrow k_c = 0.9$
  - $1/\nu$ regime limit $\rightarrow k_c = 3.5$
- **V_{ϕ}^{0} = experimental offset rotation**
- **Values of $k_c(\rho)$ fall within theoretical limits for ν and $1/\nu$ regimes**



$$k_c = \frac{V_{\phi}^{0}}{\frac{1}{Z_i e B_{\theta}} \frac{dT_i}{dr}}$$

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Dominant Scaling Factors in Neoclassical NRMF Torque Depend on Collisionality Regime

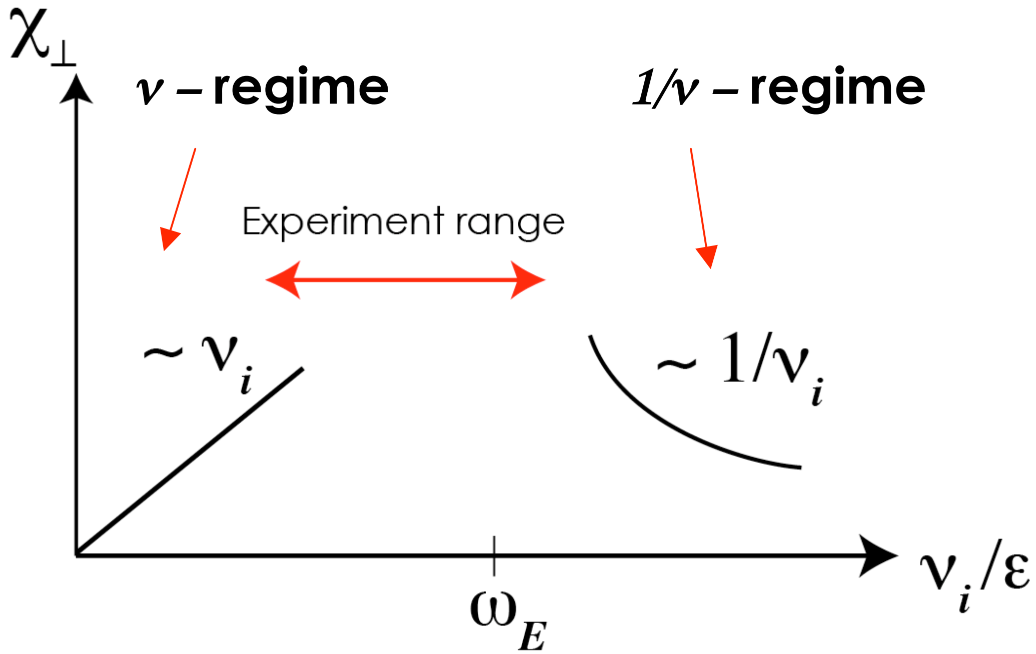
- **Low collisionality ν-regime:**

$$T_{NRMF,\nu} \propto \delta B^2 (V_\phi - V_\phi^{0,NC})\ n_i T_i^{-1/2} \omega_E^{-2}$$

- **Higher collisionality $1/\nu$-regime:**

$$T_{NRMF,1/\nu} \propto \delta B^2 (V_\phi - V_\phi^{0,NC})\ n_i^{-1} T_i^{5/2}$$

- δB = magnetic perturbation $\propto \delta I_{I\text{-}coil}$



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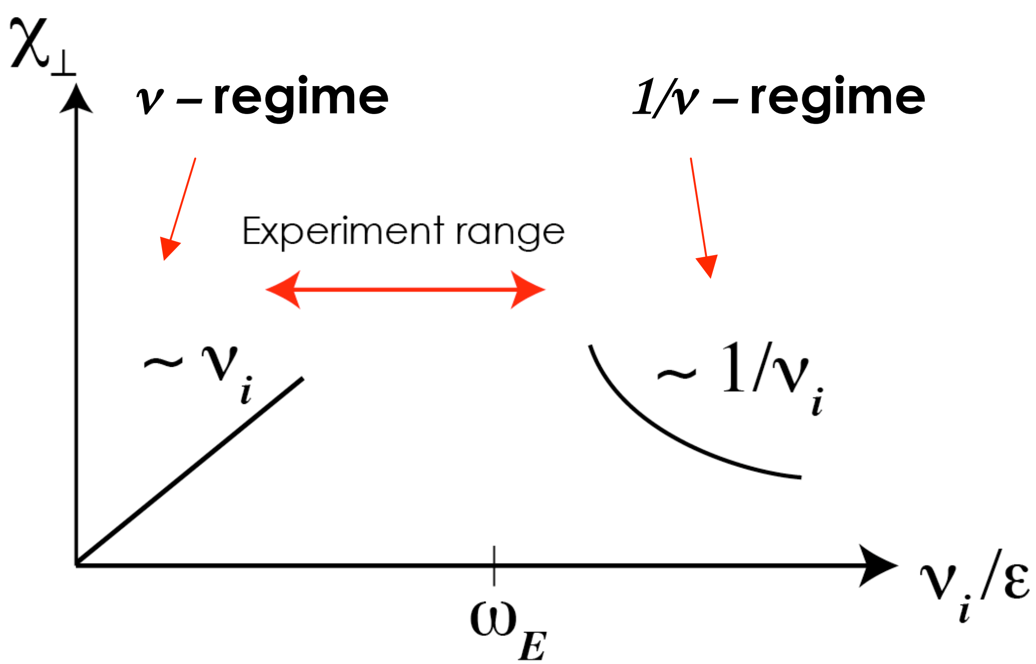
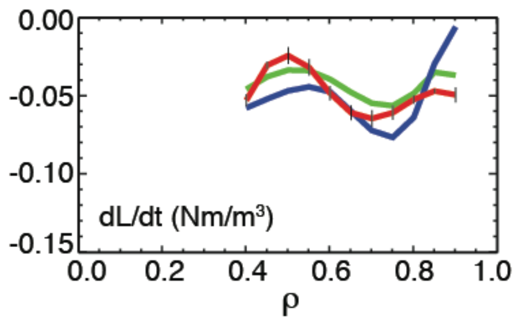


Exponents

	ν		$1/\nu$
$\delta I_{I\text{-}coil}$	2		2
$V_\phi - V_\phi^{0,NC}$	1		1
ω_E	-2		0
n_i	1		-1
T_i	-0.5		2.5

Density Scan at Constant Beta Shows Nearly Constant NRMF Torque

- **Fast, co-Ip rotation discharges**
  - ν regime of collisionality
- **~constant β_N**
- **±25% variation in density and temperature between discharges**
  - Torque profile is ~constant



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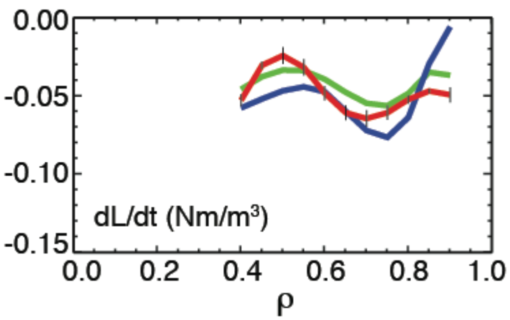
- **Normalize torque profiles to a reference discharge following different parameter dependencies**



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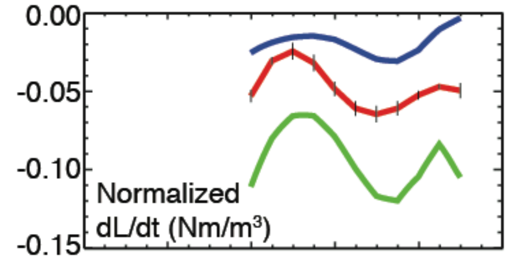
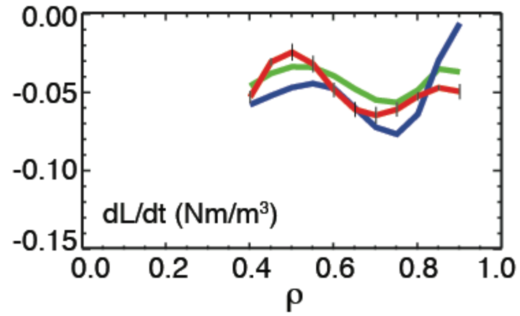
  - $1/\nu$ regime: $T_{NRMF} \sim n_i^{-1} T_i^{5/2} V_\phi$

$$T_{1/\nu} \propto \frac{T_i^{5/2}}{n_i} V_\varphi$$





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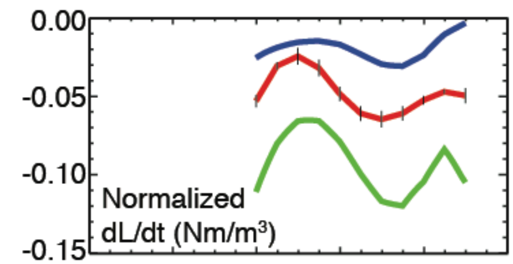
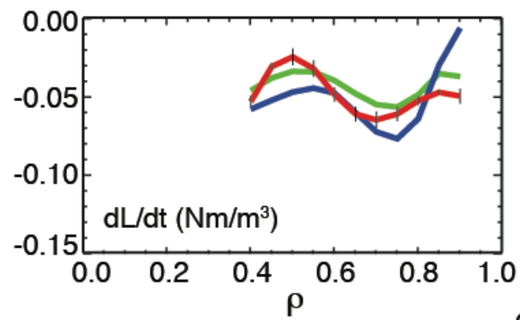
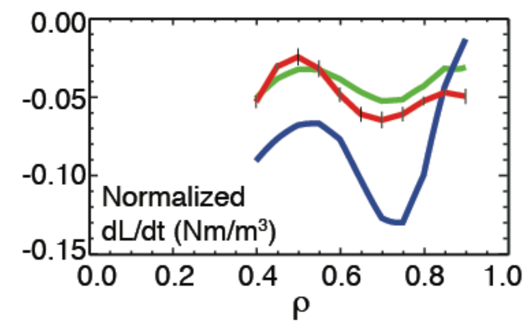
  - ν regime: $T_{NRMF} \sim n_i T_i^{-1/2} V_\phi$

$$T_{1/\nu} \propto \frac{T_i^{5/2}}{n_i} V_\varphi$$





$$T_{\nu} \propto \frac{n_i}{T_i^{1/2}} V_\varphi$$



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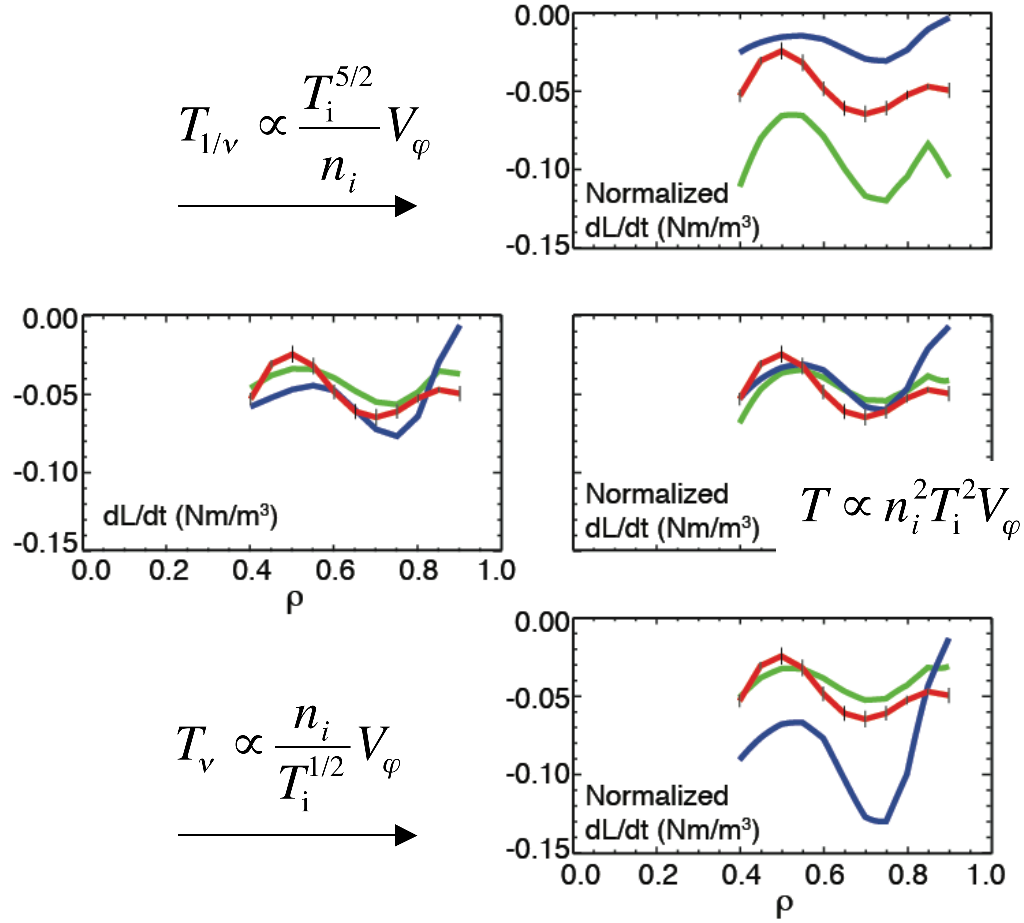
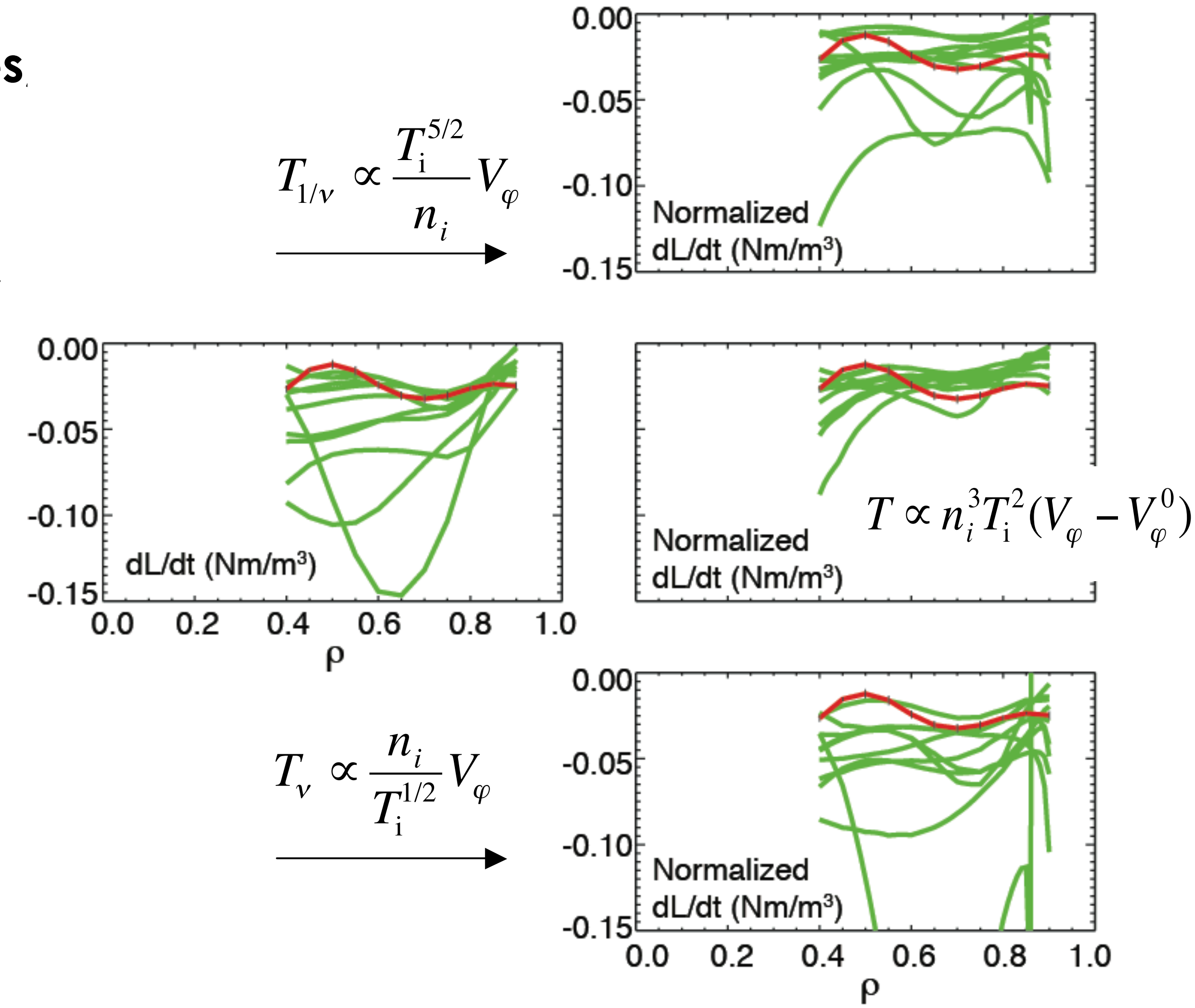
  - ν regime of collisionality
- **~constant β_N**
- **±25% variation in density and temperature between discharges**
  - Torque profile is ~constant
- **Normalize torque profiles to a reference discharge following different parameter dependencies**
  - 1/ν regime: $T_{NRMF} \sim n_i^{-1} T_i^{5/2} V_\phi$
  - ν regime: $T_{NRMF} \sim n_i T_i^{-1/2} V_\phi$
  - $T_{NRMF} \sim n_i^2 T_i^2 V_\phi$: adequate parameter dependence



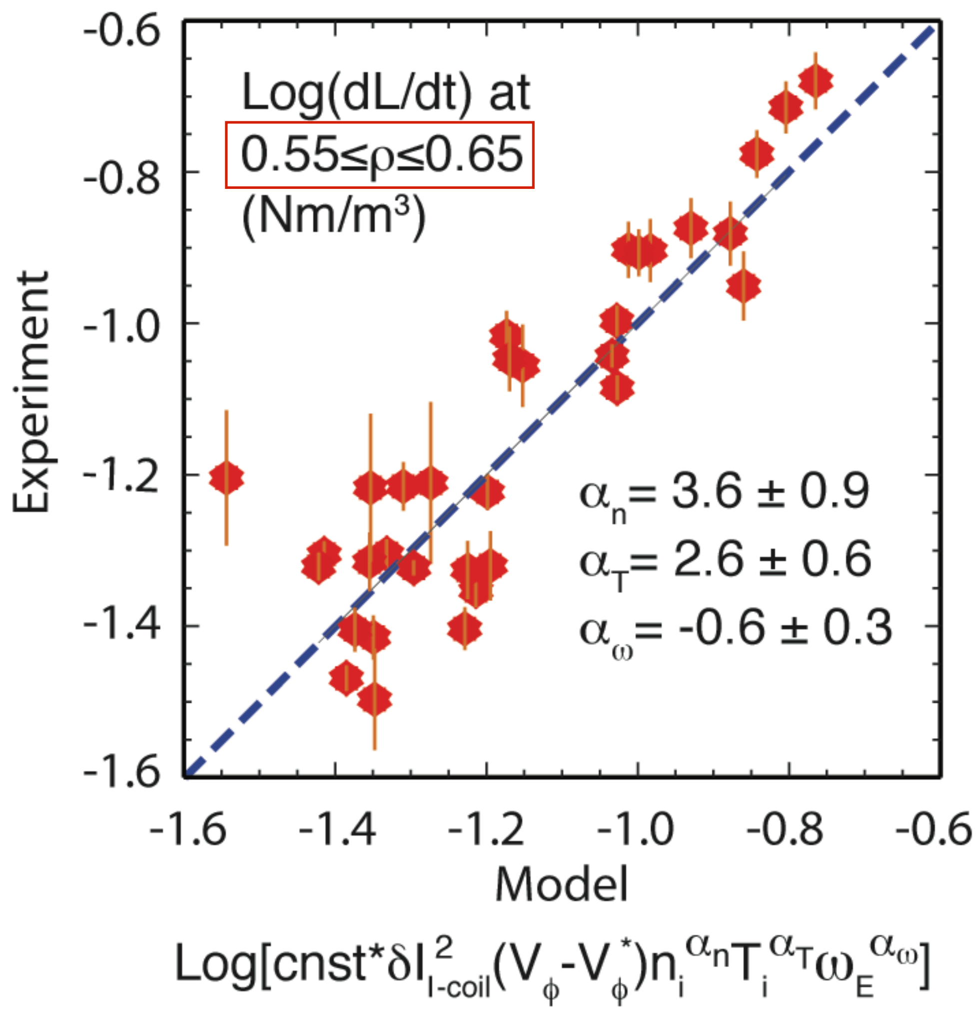
Larger Database Suggests NRMF Torque Proportional to $(nT)^2$ or $(nT)^3$

- **Co-Ip rotation discharges, ±20% variation in V_ϕ**
- **±15% variation in β_N**
- **±25% variation in density and temperature**
  - Discharges with lower rotation require including V_ϕ^0 for adequate parameter dependence

    $T_{NRMF} \sim n_i^3 T_i^2 (V_\phi - V_\phi^0)$



Database Analysis Shows Strong Dependence of NRMF Torque on n_i, Above Expected



- Co-I_p rotation discharges
- ±20% variation in V_ϕ
- ±15% variation in β_N
- ±25% variation in n_i and T_i

	ν	Exp.	1/ν	
$\delta I_{I\text{-}coil}$	2	2	2	
$V_\phi - V_\phi^{0,NC}$	1	1	1	
ω_E	-2	-0.6	0	✔
n_i	1	3.6	-1	🚫
T_i	-0.5	2.6	2.5	✔

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Measured Plasma Response to External n=3 Field Shows Significant β-dependence

- **Magnetic measurements:**

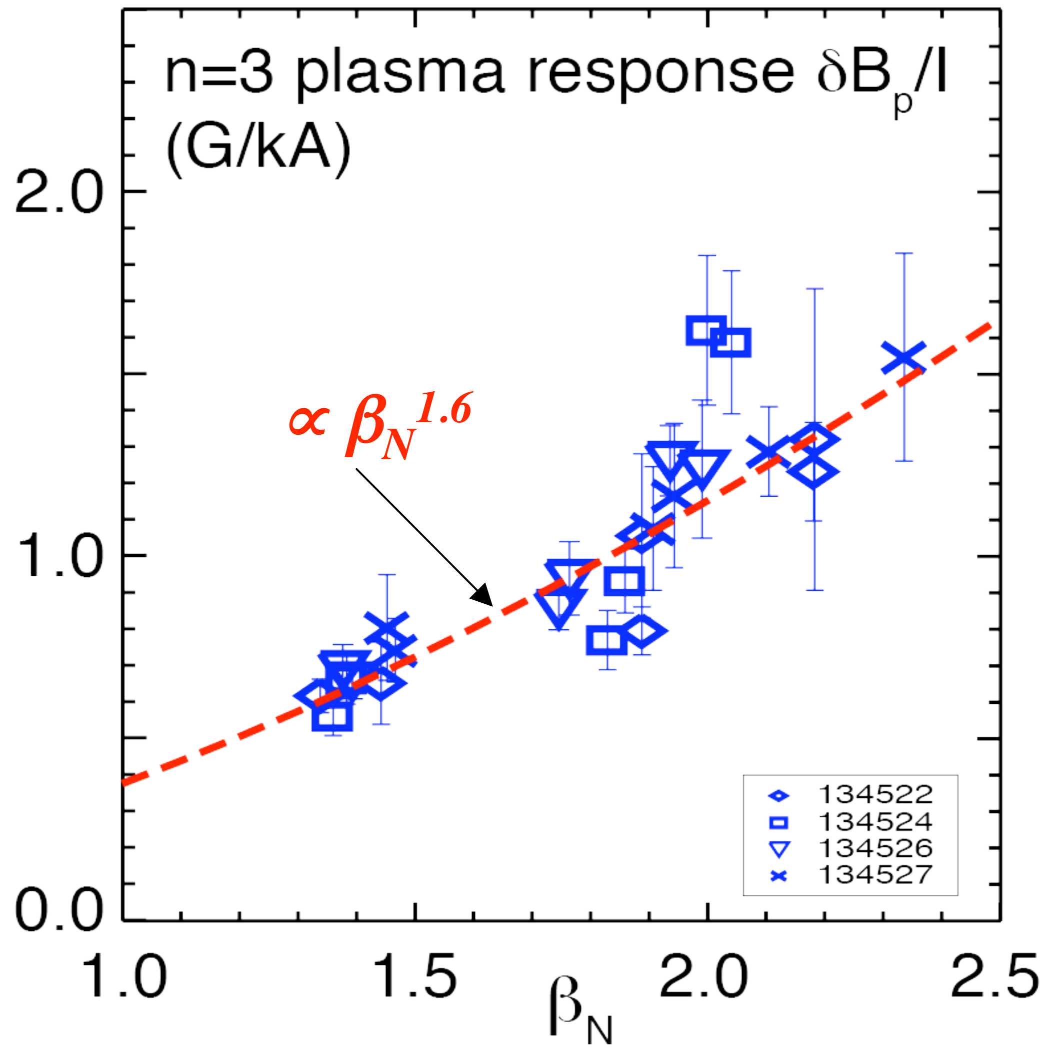
$$\delta B^{plasma} \propto \delta I_{I\text{-}coil}\, \beta_N^{1.6}$$

- **If** $\delta B^{plasma} > \delta B^{external}$ **(inside plasma):**

$$\delta B^2 = (\delta B^{pl} + \delta B^{ext})^2 \sim (\delta B^{pl})^2$$

$$\propto (\delta I_{I\text{-}coil}\, \beta_N^{1.6})^2$$

$$\sim (\delta I_{I\text{-}coil})^2\, (n_i T_i)^{3.2}$$



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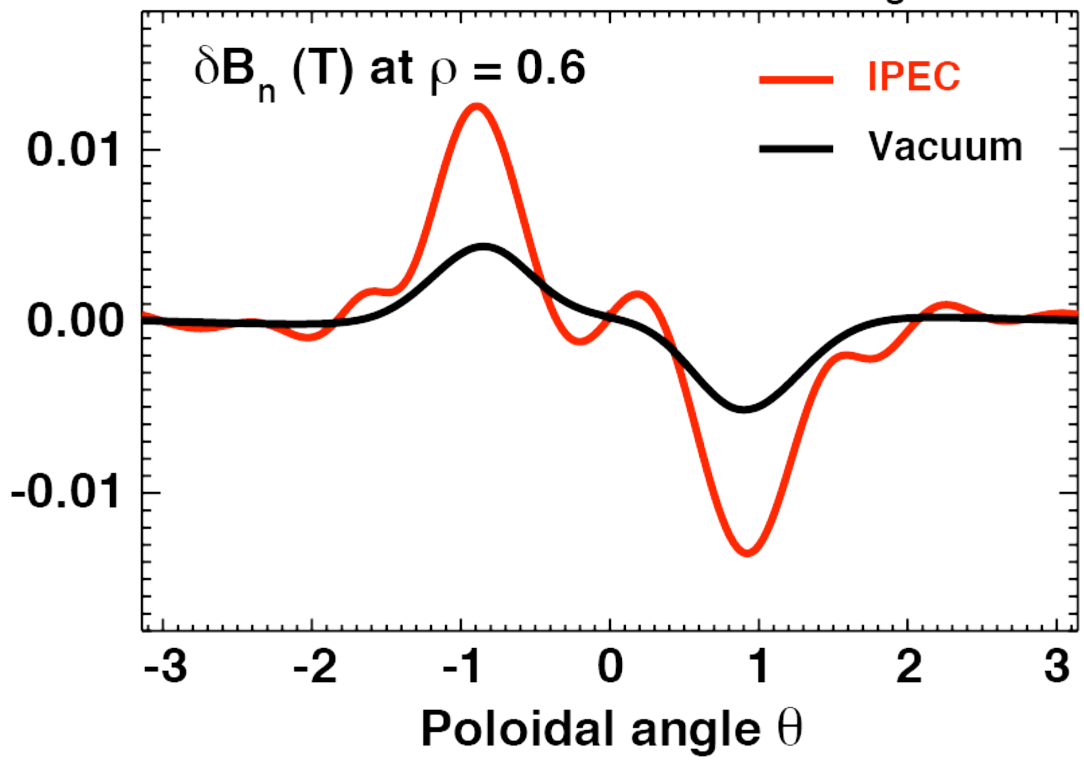
Ideal MHD Modeling Supports Hypothesis That $\delta B^{plasma} > \delta B^{external}$ Inside Plasma

- **IPEC simulation of n=3 mode excitation by I-coil**
  - [IPEC is based on DCON and VACUUM stability codes] [Park, Boozer, and Glasser, Phys. Plasmas (2007)]

- $\beta_N = 1.8 \ll \beta_N^{no\text{-}wall,n=3} \sim 2.7$

DIII-D discharge 131321



Park, GI1.00005, Tuesday AM

Modifications of Model to Account for Plasma Response

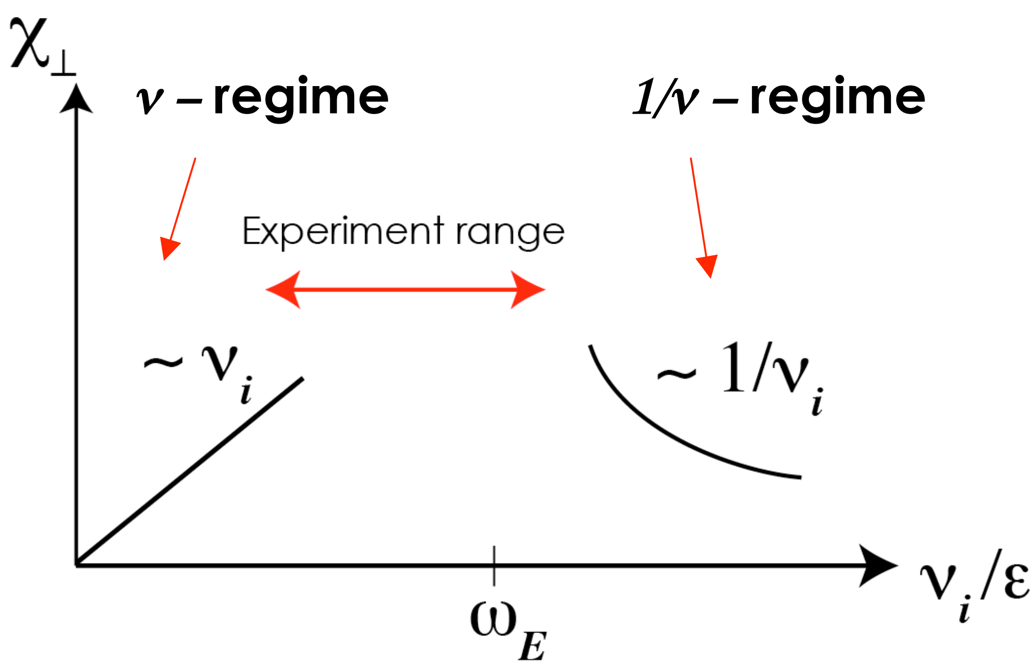
- **Low collisionality ν-regime:**

$$T_{NRMF,\nu} \propto \delta B^2 \,(V_\phi - V_\phi^{0,NC})\, n_i T_i^{-1/2} \omega_E^{-2}$$

- **Higher collisionality $1/\nu$-regime:**

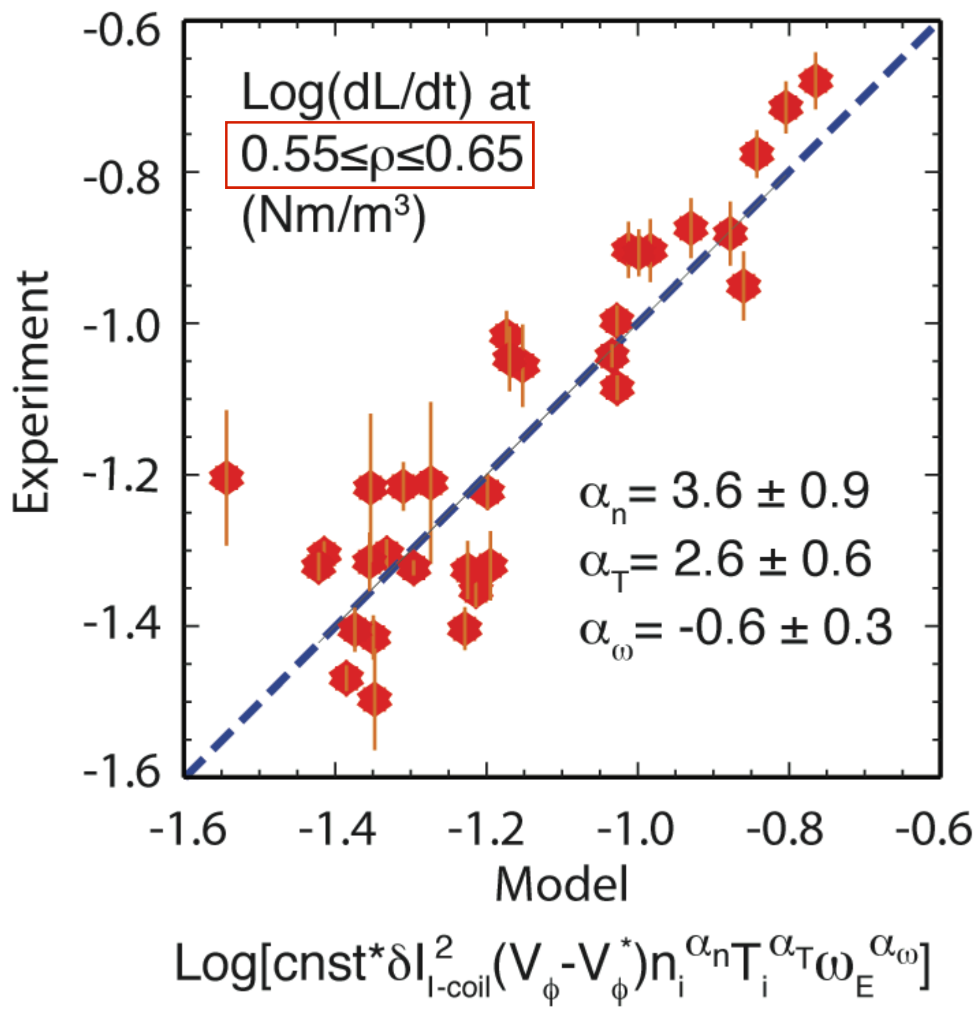
$$T_{NRMF,1/\nu} \propto \delta B^2 \,(V_\phi - V_\phi^{0,NC})\, n_i^{-1} T_i^{5/2}$$

- δB = *magnetic perturbation* $\propto \delta I_{I\text{-}coil}\,(n_i T_i)^{1.6}$



	ν	*Exp.*	$1/\nu$
$\delta I_{I\text{-}coil}$	2	2	2
$V_\phi - V_\phi^{0,NC}$	1	1	1
ω_E	-2	-0.6	0
n_i	1+3.2	3.6	-1+3.2
T_i	-0.5+3.2	2.6	2.5+3.2

Empirical Scalings Within Theoretical Limits for ν and $1/\nu$ Regimes, with Modifications for Plasma Response



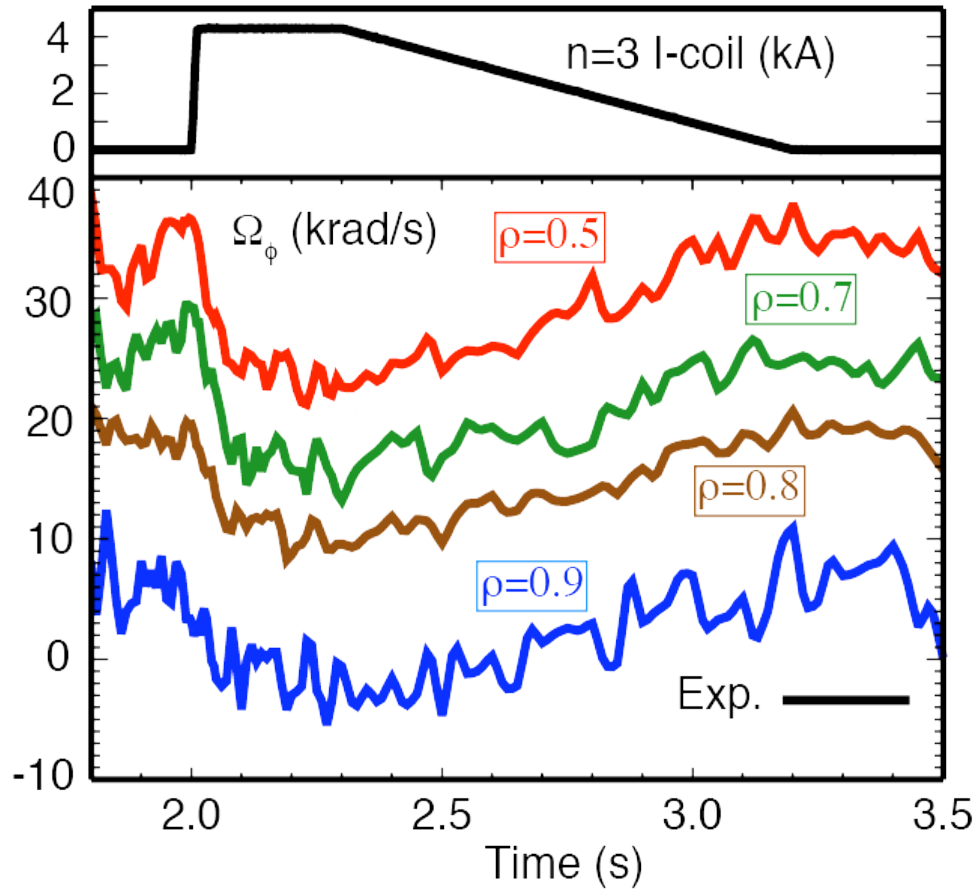
- Co-I_p rotation discharges
- ±20% variation in V_ϕ
- ±15% variation in β_N
- ±25% variation in n_i and T_i

	ν	*Exp.*	$1/\nu$
$\delta I_{I\text{-}coil}$	2	2	2
$V_\phi - V_\phi^{0,NC}$	1	1	1
ω_E	-2	-0.6	0
n_i	4.2	3.6	2.2
T_i	2.7	2.6	5.7

Rotation Profile Evolution Consistent with Measured Torque Varied According to Empirical Scalings

- **Evolve measured torque profile according to:**

$$T_{NRMF} \propto \delta I_{Ic}^{2} (V_{\phi} - V_{\phi}^{0,NC})^{1} n_i^{3.6} T_i^{2.6} \omega_E^{-0.6}$$



Rotation Profile Evolution Consistent with Measured Torque Varied According to Empirical Scalings

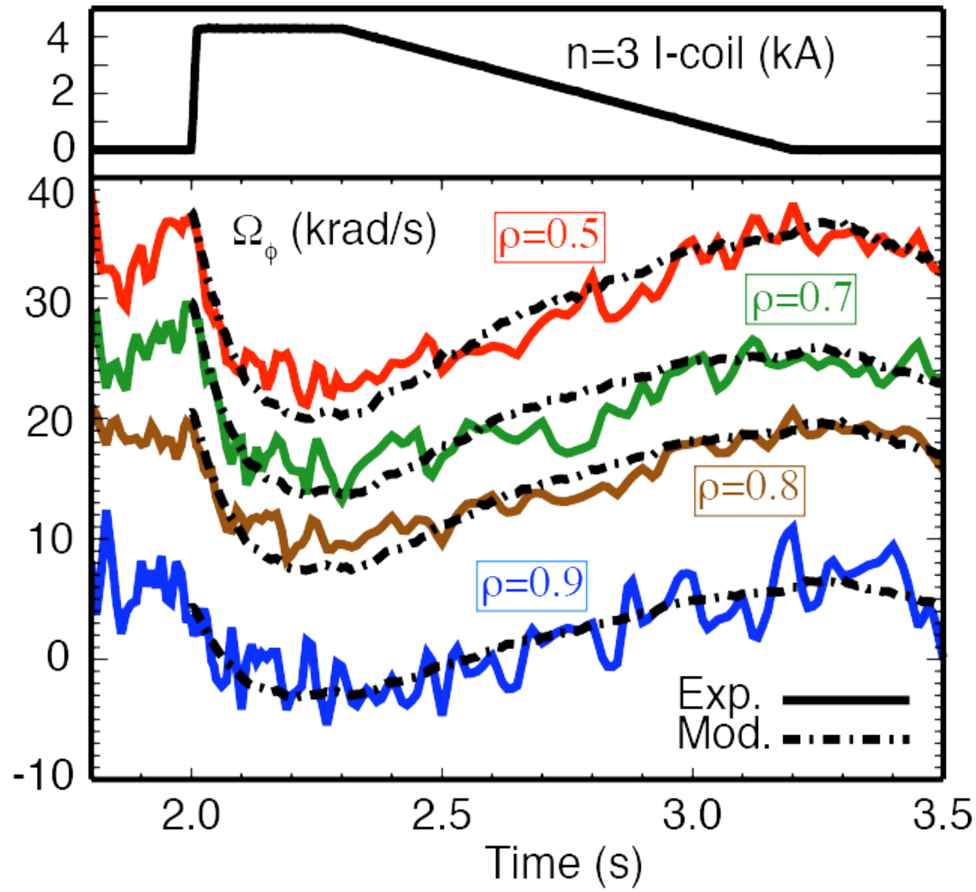
- **Evolve measured torque profile according to:**

$$T_{NRMF} \propto \delta I_{Ic}^{2} (V_{\phi} - V_{\phi}^{0,NC})^{1} n_i^{3.6} T_i^{2.6} \omega_E^{-0.6}$$

- **Simulate rotation evolution using momentum balance in TRANSP**

$$mnR \frac{\partial V_{\phi}}{\partial t} = \sum T + \nabla \cdot \left(mnR\chi_{\phi} \frac{\partial V_{\phi}}{\partial r} \right)$$

- **Use momentum diffusivity χ_{ϕ} from evolution without NRMF**



Outline

- Evidence of offset rotation
- Comparison to neoclassical prediction
- Analysis of torque scaling
- Role of plasma response
- Implications for ITER

Large NRMF Torque Is Associated with High-*n* Fields Planned for ELM Suppression in ITER

- **Expected NRMF damping time from ELM-suppression fields:**

  τ_{dam} **~ 10 ms**

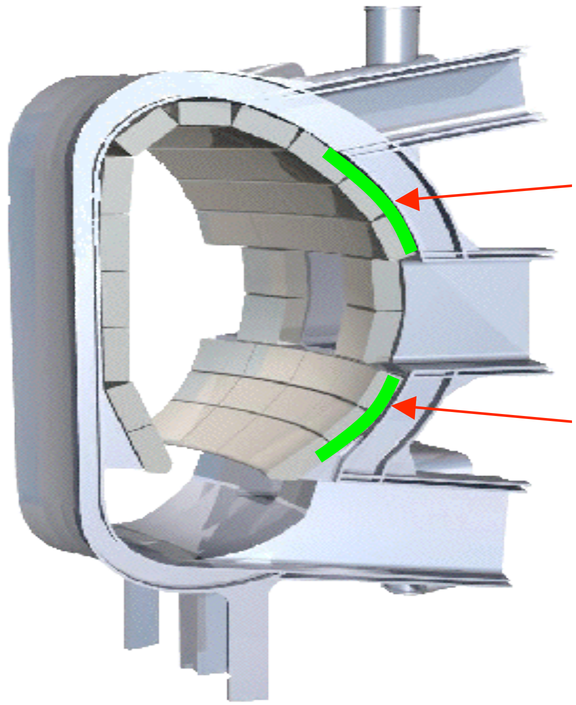
  [Becoulet et al., IAEA (2008)]

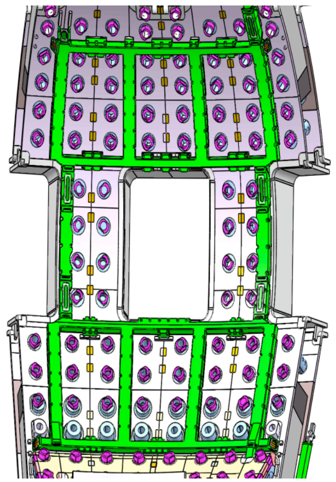
  τ_{dam} **~ 10-100 ms**

  [Park et al., IAEA (2008)]

- **Rotation in ITER will depend on** T_{NRMF} / T_{NBI} **(=** τ_L / τ_{dam}**)**
  - $\tau_L \sim \tau_E = 3.7$ s

- T_{NRMF} **~ 40-400x** T_{NBI}

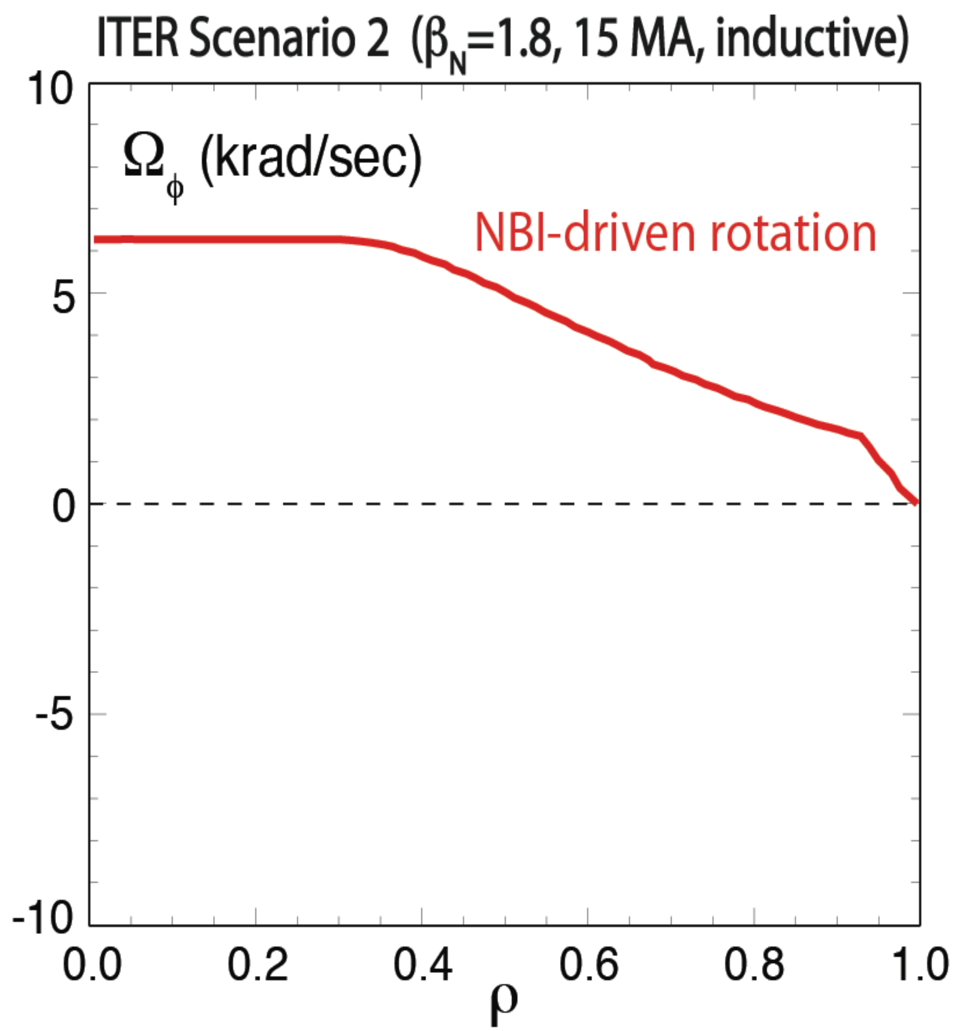




T_{NRMF} >> T_{NBI} in ITER May Force Plasma Flow in Counter-Ip Direction, Close to "Offset" Rotation

- **NBI-driven rotation from ASTRA Code simulation**

  [Polevoi et al., Nucl. Fusion (2005)]

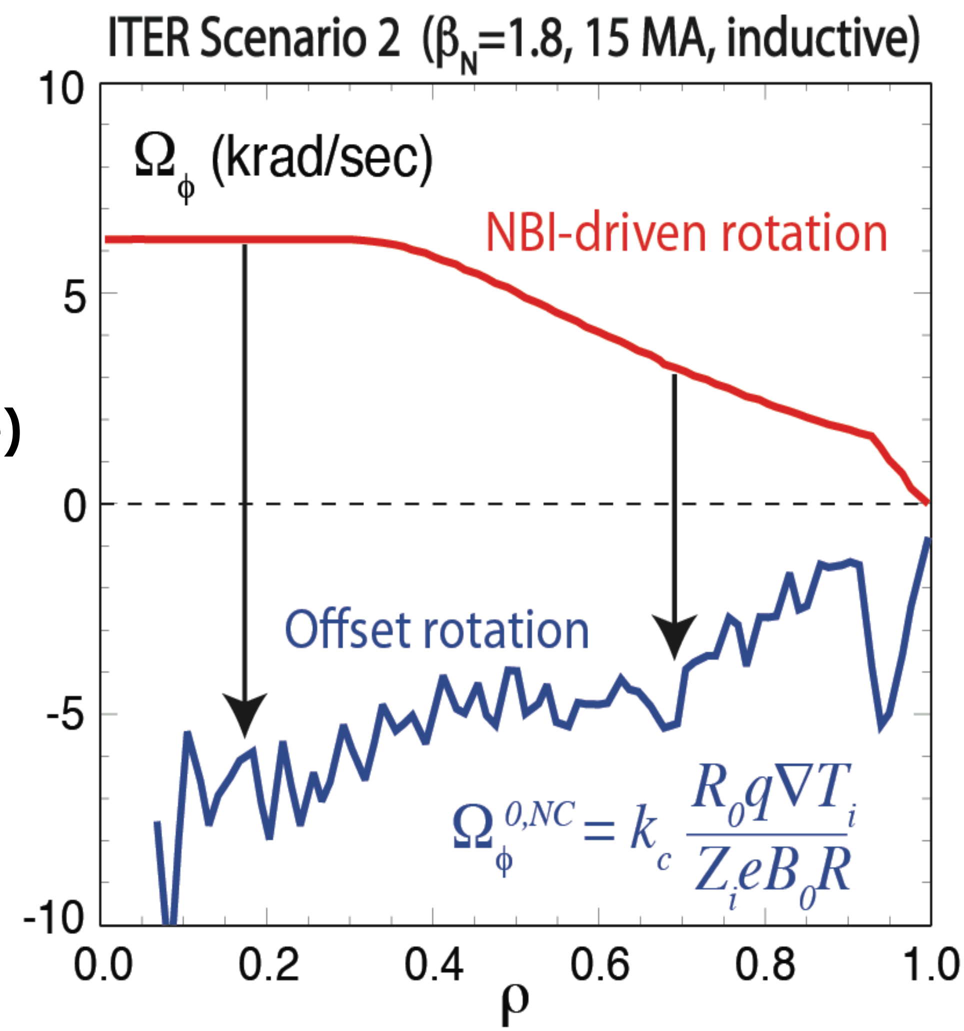


$T_{NRMF} \gg T_{NBI}$ in ITER May Force Plasma Flow in Counter-Ip Direction, Close to "Offset" Rotation

- **NBI-driven rotation from ASTRA Code simulation**

  [Polevoi et al., Nucl. Fusion (2005)]

- **Neoclassical offset rotation with k_c from DIII-D experiments (ν-regime)**
  - $\Omega_\phi^{0,NC} \sim 0.4\% \Omega_A$
  - May be sufficient to benefit confinement and stability



Summary

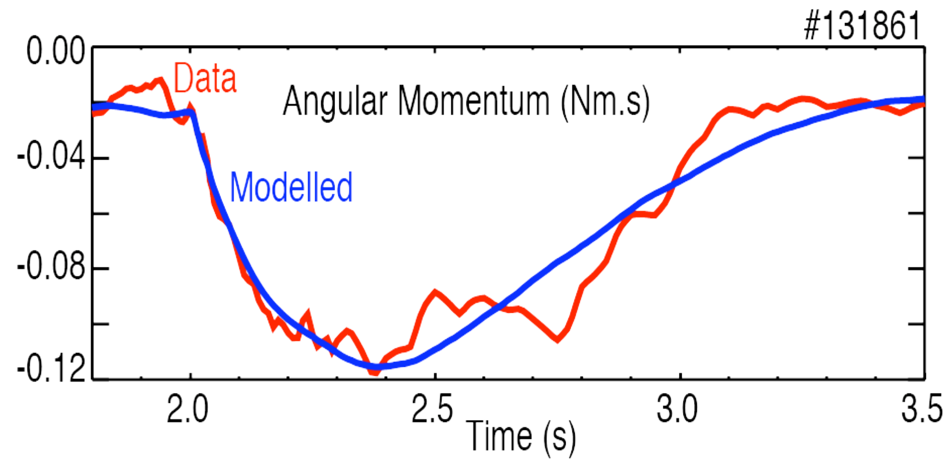
- **Evidence that static NRMF can accelerate plasma rotation toward "offset" value, consistent with neoclassical theory**
- **Observed strong dependence of NRMF torque parameter on $n_i T_i$ not consistent with neoclassical theory for vacuum calculations of external NRMF**
  - Experiment and theory can be consistent if plasma response to NRMF dominates over external field inside plasma
  - Observed β-dependence of plasma response can account for strong NRMF torque dependence on $n_i T_i$
- **ELM suppression fields in ITER may force counter-Ip (rapid) rotation, even with co-Ip NBI**

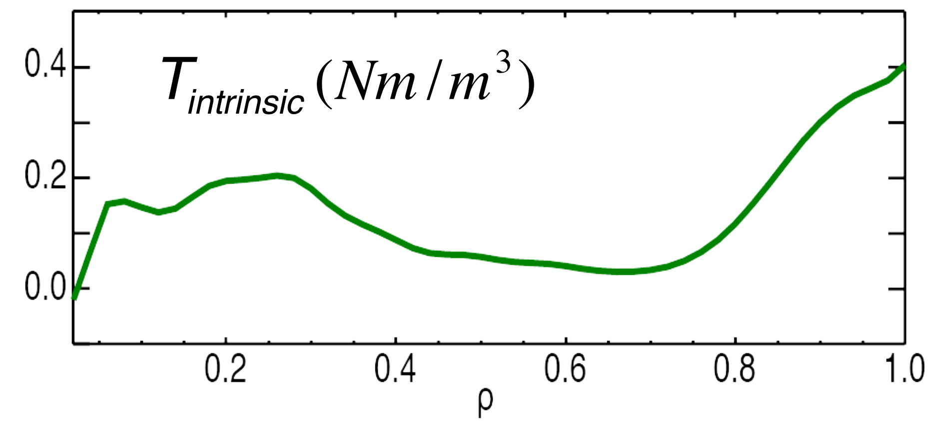
Backup Slides …

At Lower NBI Torque, Modeling of NRMF Torque Has to Account for Intrinsic Rotation

- **Evolve measured T_{NRMF} profile from initial step according to $\delta I_{Ic}^2(V_\phi - V_\phi^{0,NC})$**
- **Assume intrinsic momentum source is constant in time**
- **Allow variation of $\tau_\phi \propto \tau_i$**
- **For each ρ, solve for intrinsic source which gives best fit to L data**
- **Intrinsic momentum source profile similar to previous results**

$$\int_0^\rho \frac{dL}{dt} dV = \int_0^\rho \left(-\frac{L(t)}{\tau_\phi(t)} + T_{NBI}(t) + T_{NRMF}(t) + S_{intrinsic} \right) dV$$





At Lower NBI Torque, Modeling of NRMF Torque Has to Account for Intrinsic Rotation

- **Evolve measured T_{NRMF} profile from initial step according to $\delta I_{Ic}^2(V_\phi - V_\phi^{0,NC})$**
- **Assume intrinsic momentum source is constant in time**
- **Allow variation of $\tau_\phi \propto \tau_i$**
- **For each ρ, solve for intrinsic source which gives best fit to L data**
- **Intrinsic momentum source profile similar to previous results**
  - $T_{intrinsic} = -T_{NBI}$
    for ~zero rotation profile with finite neutral beam torque
    [Solomon et al., PPCF (2007)]

$$\int_0^\rho \frac{dL}{dt}dV = \int_0^\rho \left(-\frac{L(t)}{\tau_\phi(t)} + T_{NBI}(t) + T_{NRMF}(t) + S_{intrinsic} \right) dV$$